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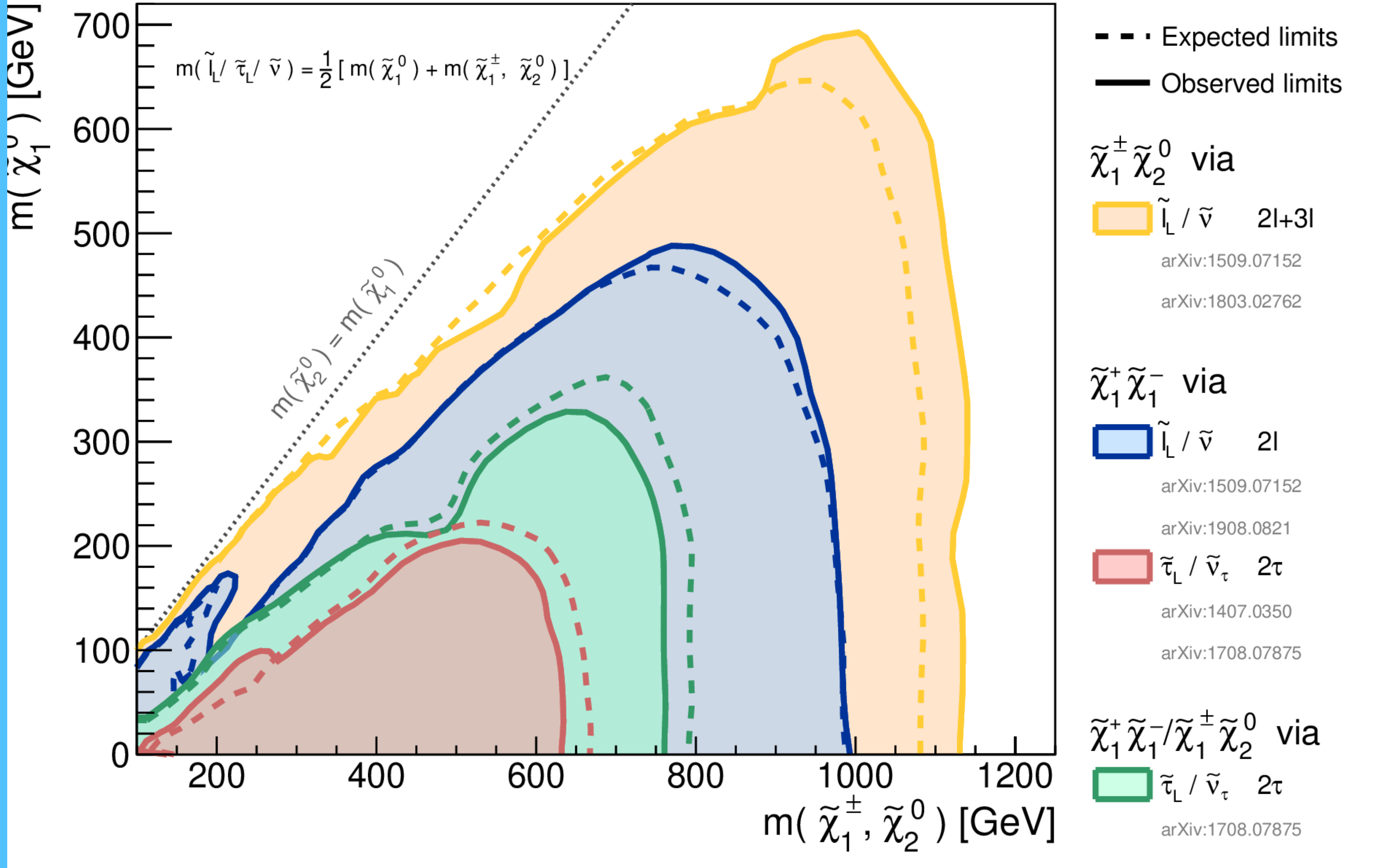
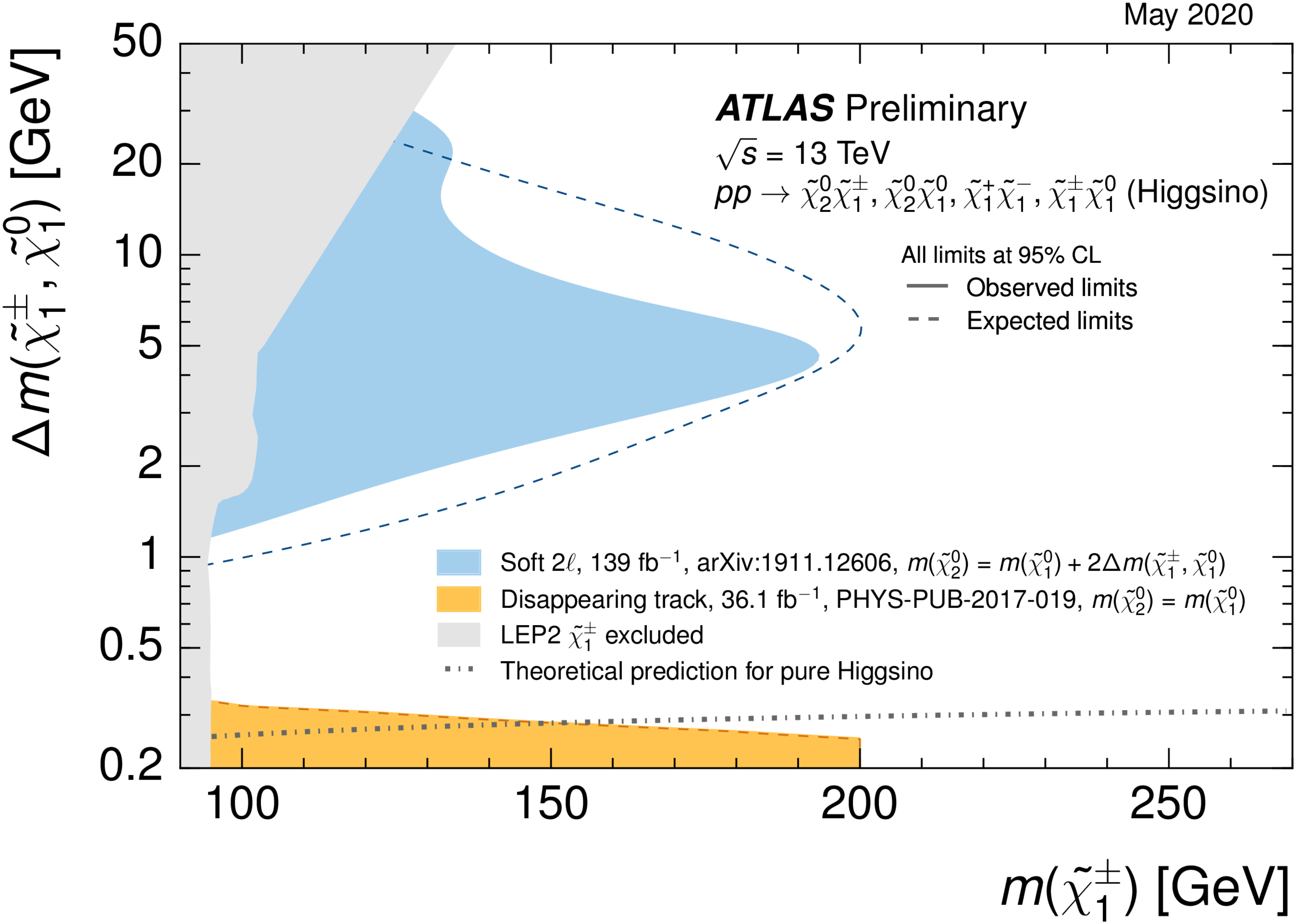
# Improved $(g-2)_\mu$ measurements and SUSY at existing and future colliders

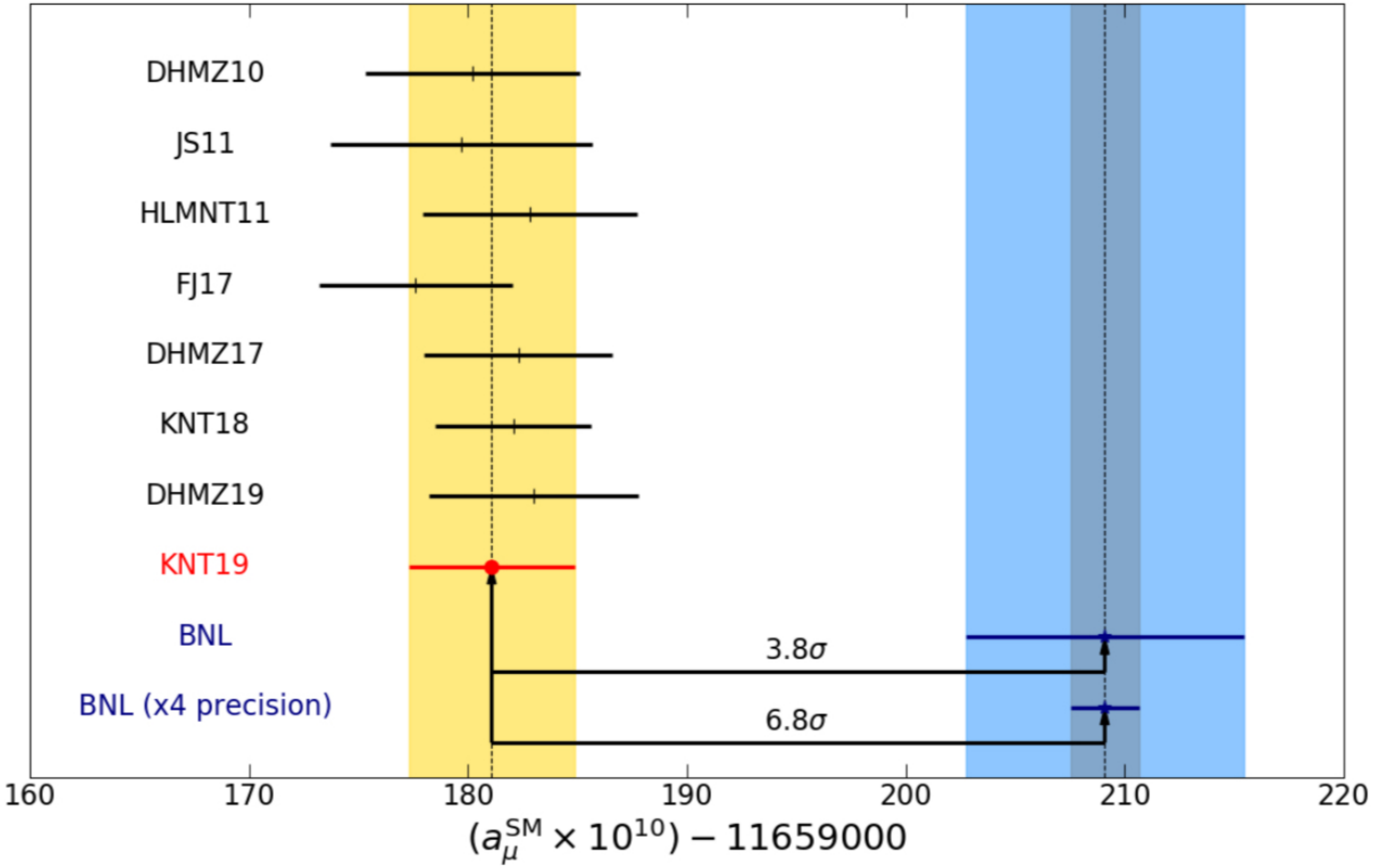
**15/03/2021** BASED ON : 2006.15157, EPJC WITH SVEN HEINEMEYER AND IPSITA SAHA

- EW sector may be hiding key to new physics
- Modest production cross section, mass bounds from the LHC comparably weak
- May show up elsewhere : DM experiments, $(g-2)_\mu$ ...
- $3.7\sigma$ discrepancy in $(g-2)_\mu$
- New results from Fermilab ‘MUON (g-2)’ coming soon !

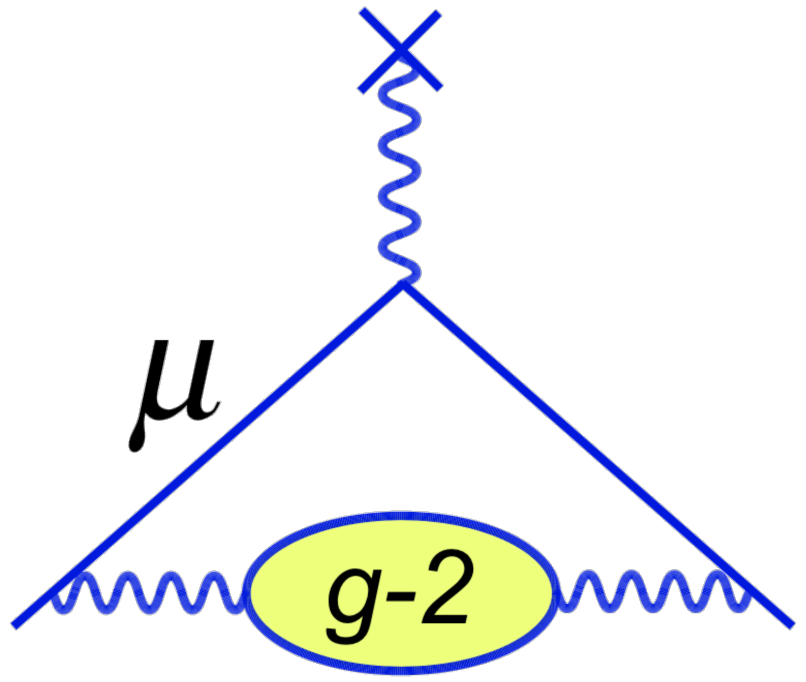




# Muon (g-2)



Keshavarzi, Nomura, Teubner '20



$$a_\mu^{exp} - a_\mu^{theo,SM} = (27.9 \pm 7.6) \times 10^{-10}$$

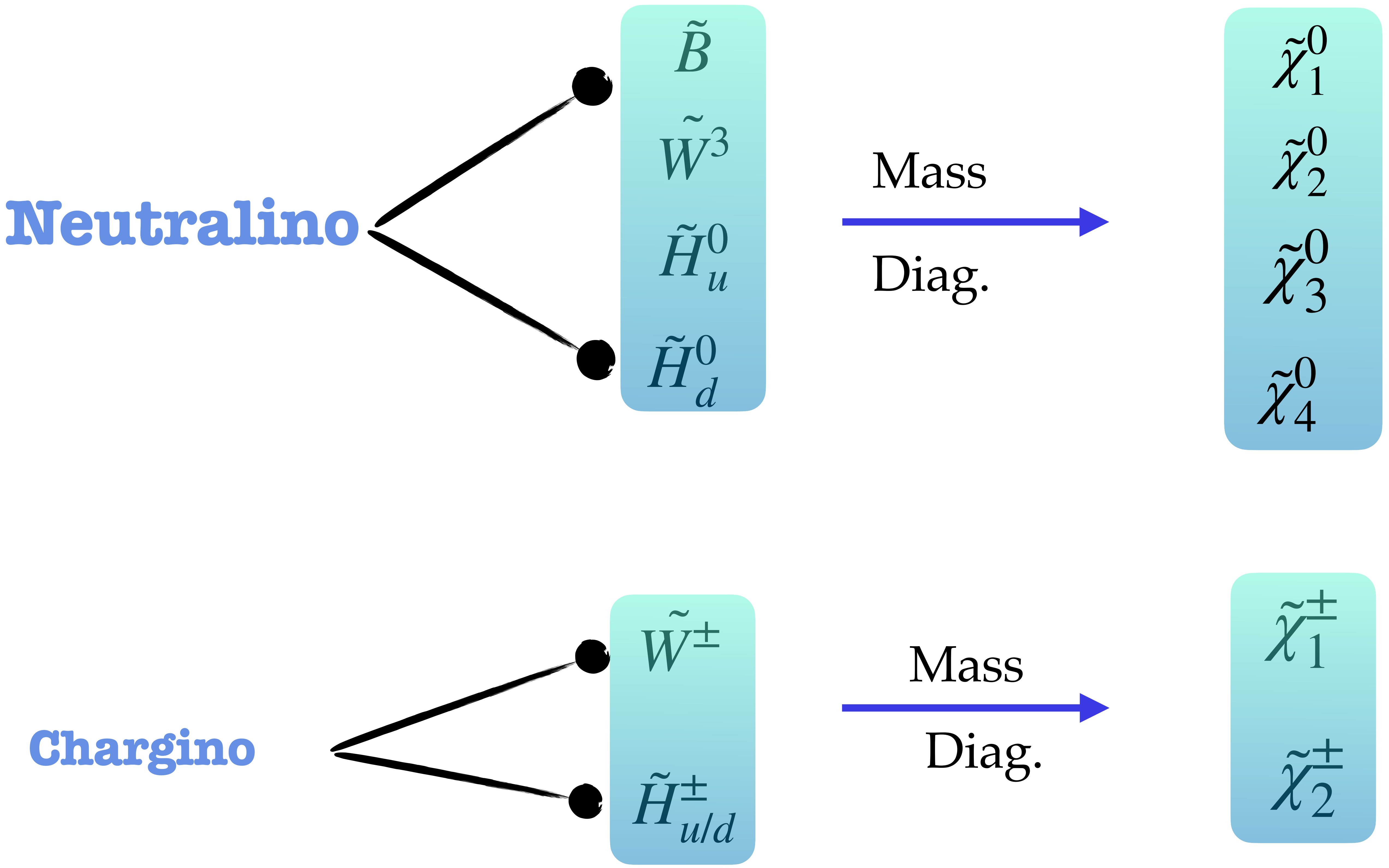
- Aoyama *et al* '20

$\sim 3.7\,\sigma$

Muon g-2 experiment at Fermilab aims at 4 x BNL precision

# EW Gauginos

Masses and mixing are determined by U(1) and SU(2) gaugino masses $M_1$, $M_2$ and Higgs mass parameter $\mu$.



**Neutralino**

$\tilde{B}$

$\tilde{W}^3$

$\tilde{H}_u^0$

$\tilde{H}_d^0$

$\xrightarrow[\text{Diag.}]{\text{Mass}}$

$\tilde{\chi}_1^0$

$\tilde{\chi}_2^0$

$\tilde{\chi}_3^0$

$\tilde{\chi}_4^0$

**Chargino**

$\tilde{W}^{\pm}$

$\tilde{H}_{u/d}^{\pm}$

$\xrightarrow[\text{Diag.}]{\text{Mass}}$

$\tilde{\chi}_1^{\pm}$

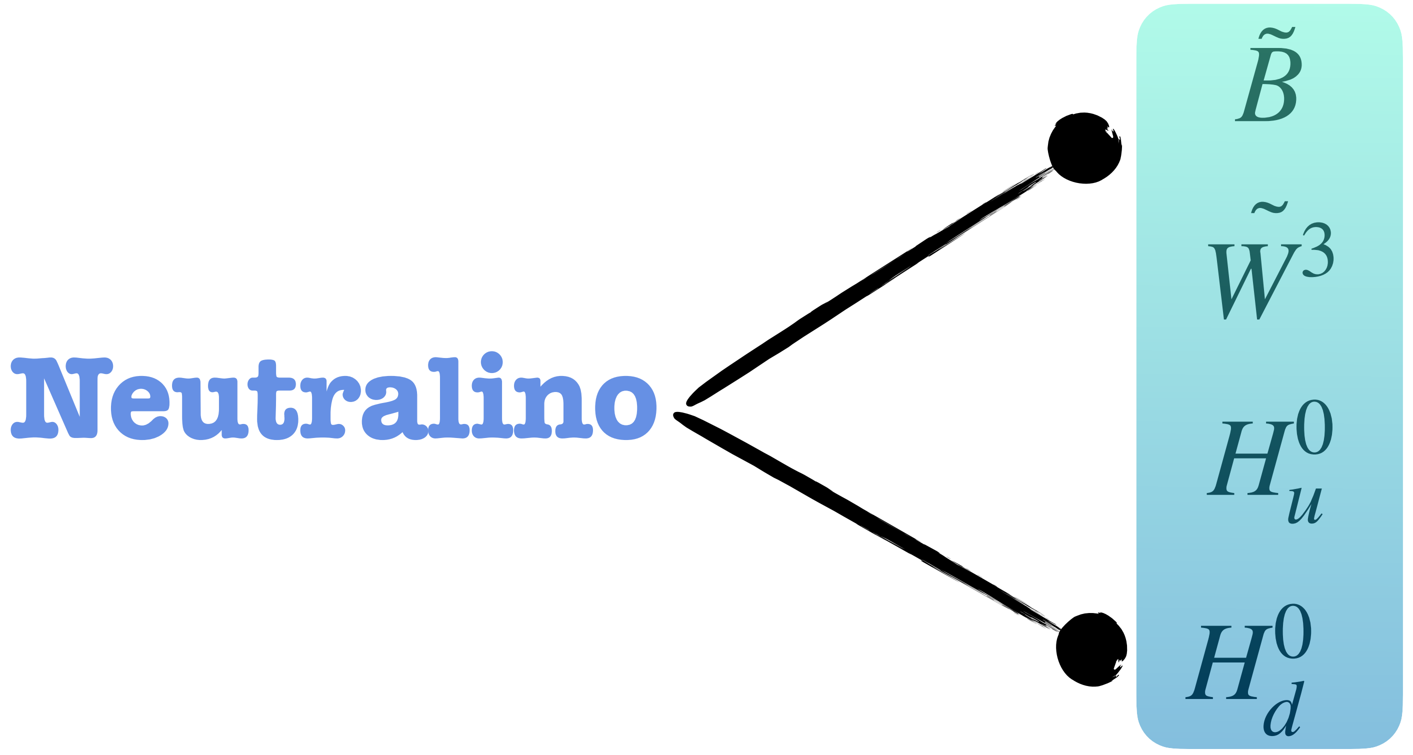
$\tilde{\chi}_2^{\pm}$

LSP in RPC

**DM**

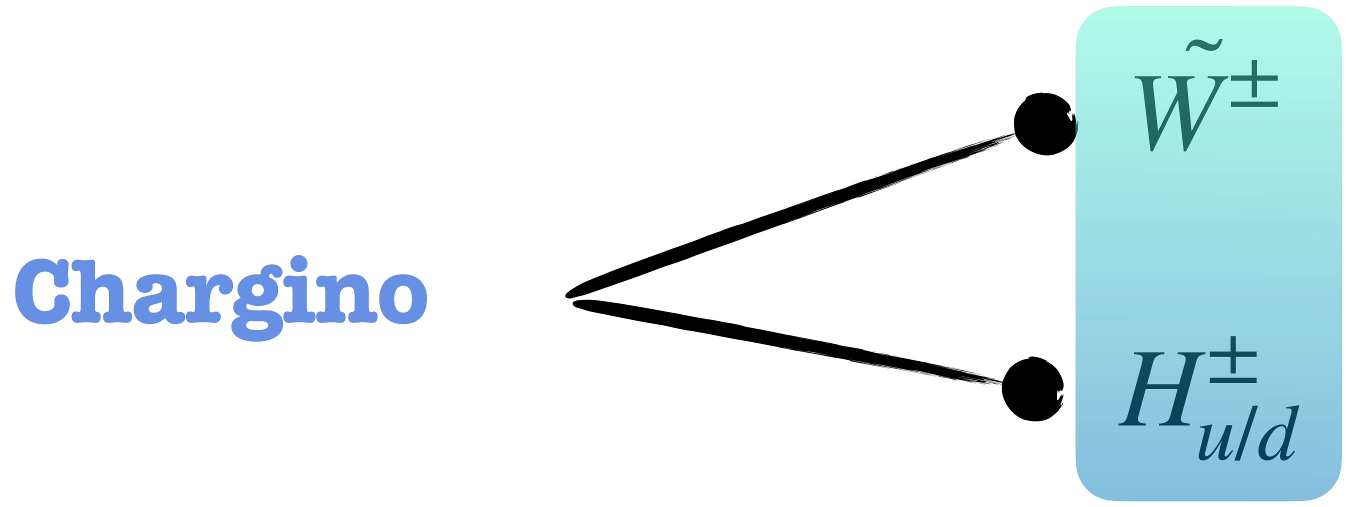
# EW Gauginos

Masses and mixing are determined by U(1) and SU(2) gaugino masses $M_1$, $M_2$ and Higgs mass parameter $\mu$.



Neutralino Mass Matrix

$$M_N = \begin{pmatrix} M_1 & 0 & -M_Z\, c_\beta\, s_W & M_Z\, s_\beta\, s_W \\ 0 & M_2 & M_Z\, c_\beta\, cW & -M_Z\, s_\beta\, cW \\ -M_Z\, c_\beta\, s_W & M_Z\, c_\beta\, c_W & 0 & -\mu \\ M_Z\, s_\beta\, s_W & -M_Z\, s_\beta\, c_W & -\mu & 0 \end{pmatrix}$$



Chargino Mass Matrix

$$M_C = \begin{pmatrix} M_2 & \sqrt{2} M_W c_\beta \\ \sqrt{2} M_W s_\beta & \mu \end{pmatrix}$$

FOUR PARAMETERS → $M_1, M_2, \mu, \tan\beta$

# Sleptons

Slepton Mass Matrix

$$M_{\tilde{L}}^2 = \begin{pmatrix} m_l^2 + m_{LL}^2 & m_l X_l \\ m_l X_l & m_l^2 + m_{RR}^2 \end{pmatrix}$$

$$m_{LL}^2 = m_{\tilde{L}}^2 + (I_l^{3L} - Q_l s_w^2) M_z^2 c_{2\beta}$$

$$m_{RR}^2 = m_{\tilde{R}}^2 + Q_l s_w^2 M_z^2 c_{2\beta}$$

$$X_l = A_l - \mu (\tan\beta)^{2I_l^{3L}}$$

**PARAMETERS** → $M_1, M_2, \mu, \tan\beta\,, m_{\tilde{L}}\,, m_{\tilde{R}}$

First two gens. $m_{\tilde{l}_1} \sim m_{LL}$ $m_{\tilde{l}_2} \sim m_{RR}$

# Constraints

**Proper recasting is important**

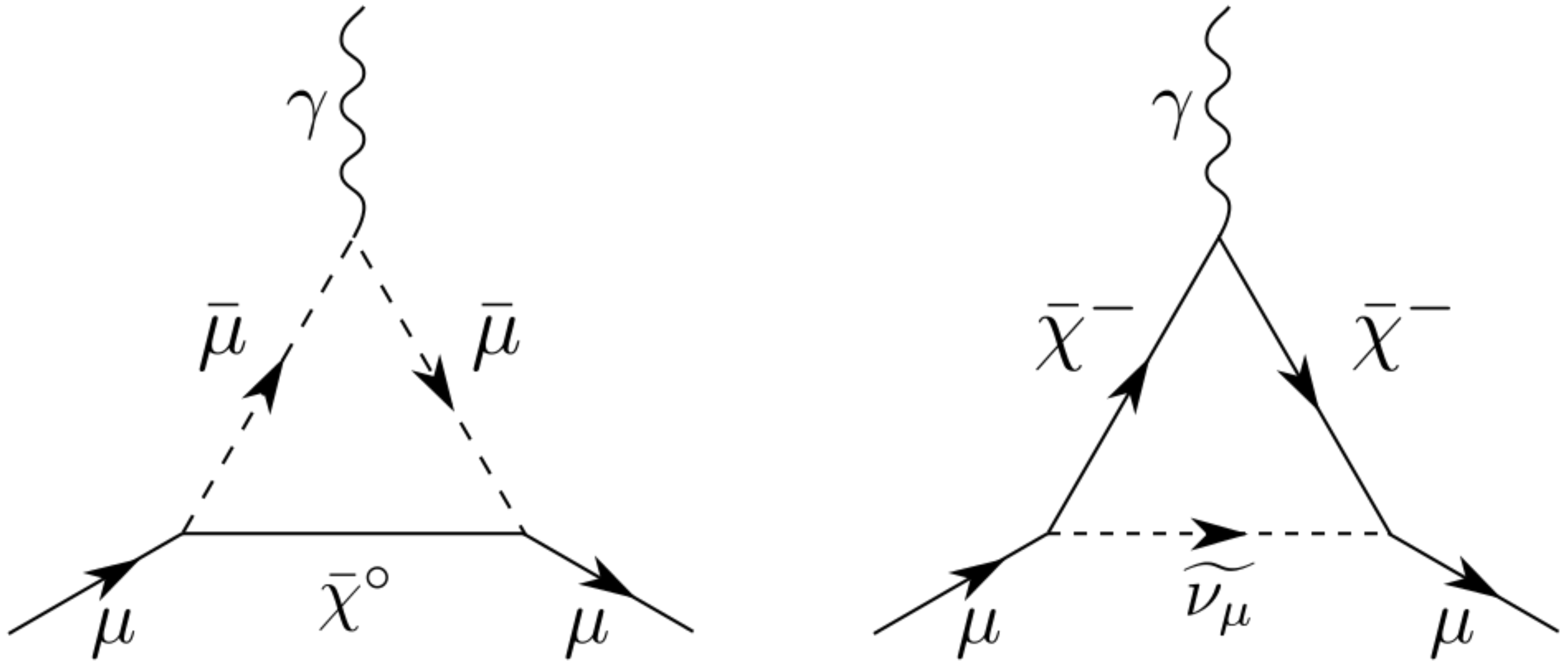
## Direct Searches at LHC

- LHC searches restricted to **simplified models.**
- $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ taken to be mass-degenerate and purely wino. $\tilde{\chi}_1^0$ purely bino.
- All three generations of sleptons and sneutrinos assumed mass degenerate.
- Heavier gauginos $\tilde{\chi}_3^0, \tilde{\chi}_4^0, \tilde{\chi}_2^{\pm}$ assumed to be decoupled.
- No sensitivity to parameters like tan $\beta$.

## Indirect Constraints

- Muon (g-2).
- WMAP/PLANCK relic density.
- Spin independent direct detection data from XENON/LUX.
- Indirect detection constraints of dark matter.

# Muon (g-2) in MSSM



- SUSY contributions from Chargino-Sneutrino and Smuon-Neutralino loop
- SM EW 1 loop : $\frac{\alpha}{\pi}\frac{m_\mu^2}{M_W^2}.$ MSSM , 1 loop : $\frac{\alpha}{\pi}\frac{m_\mu^2}{M_{SUSY}^2} \times tan\beta$
- SUSY can easily explain anomaly !

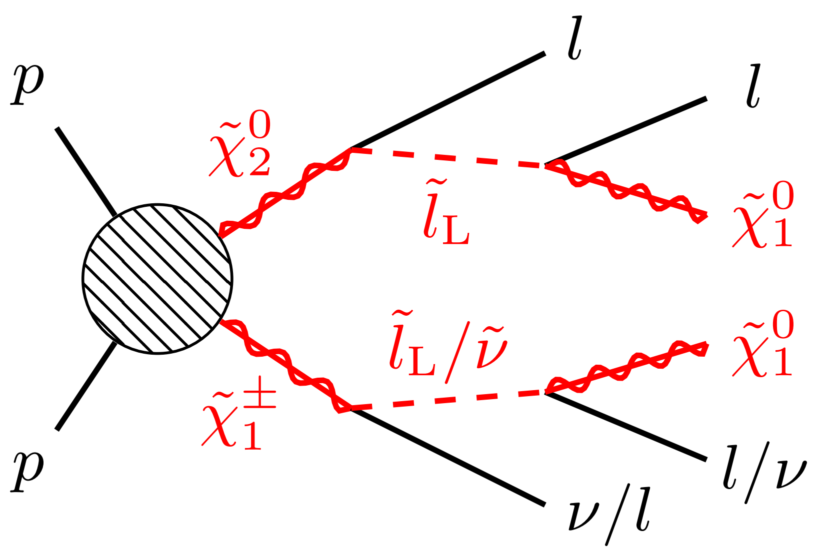
upper limits on EW super partner masses

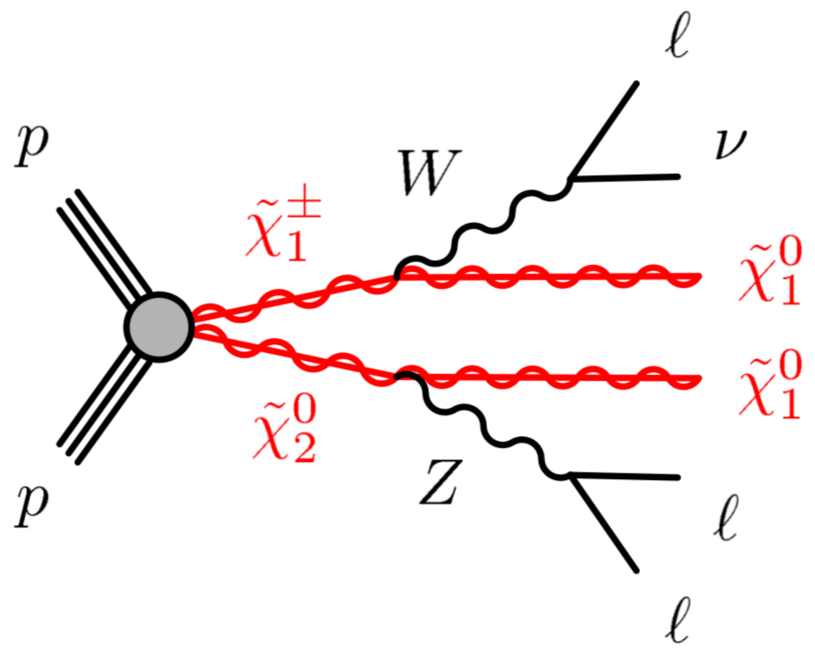
# Searches at the LHC

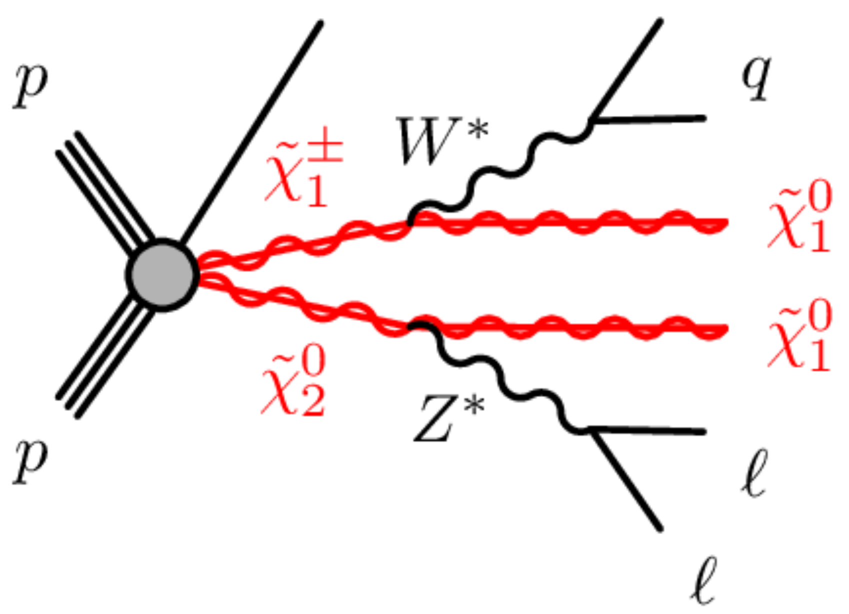
- Trilepton searches

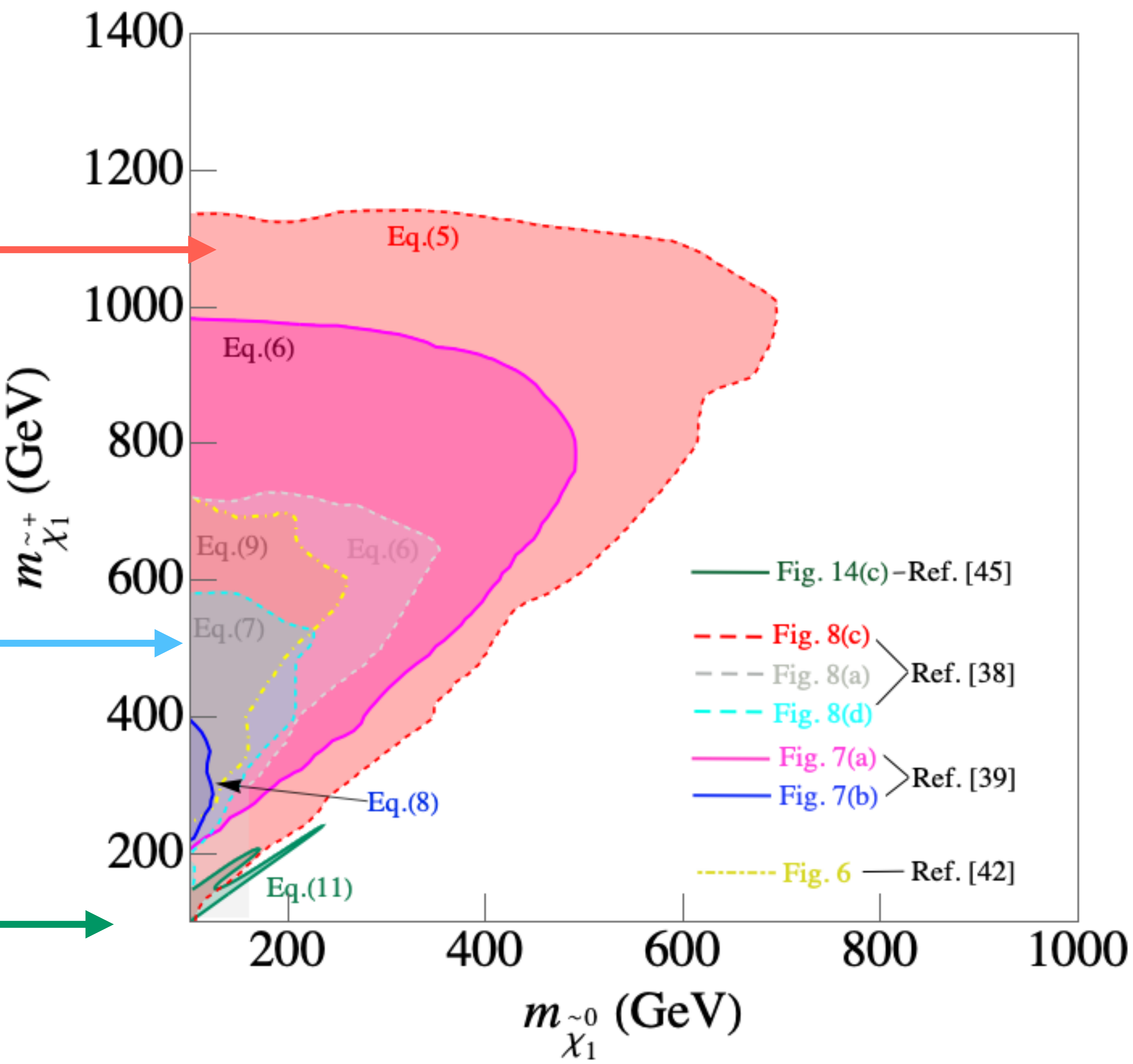
  ATLAS [1803.02762]

  13 TeV, 36 $fb^{-1}$









- Compressed spectra searches

  ATLAS 1911.12606

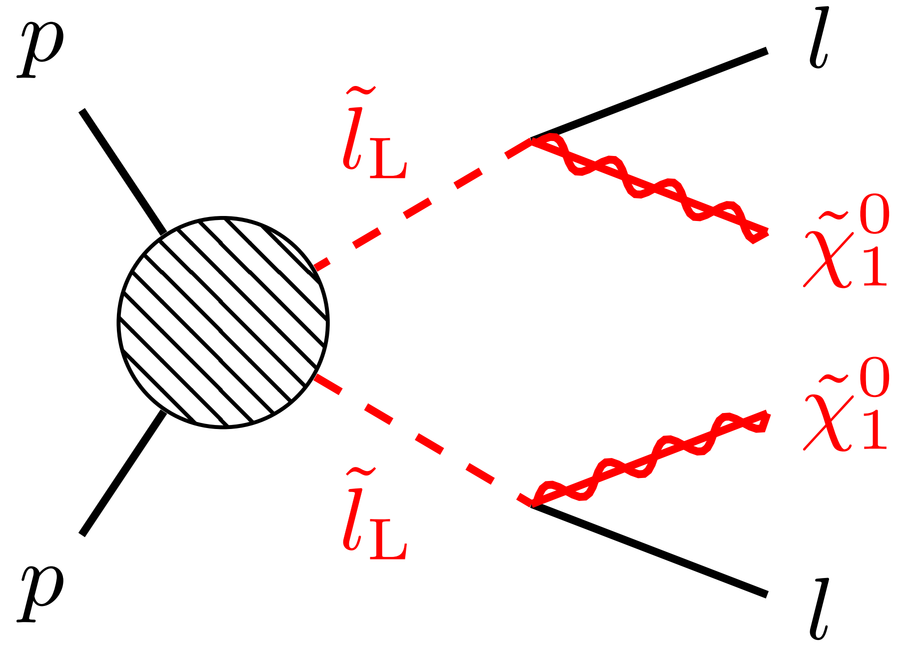
Proper recasting is important ⟶ **checkMATE**

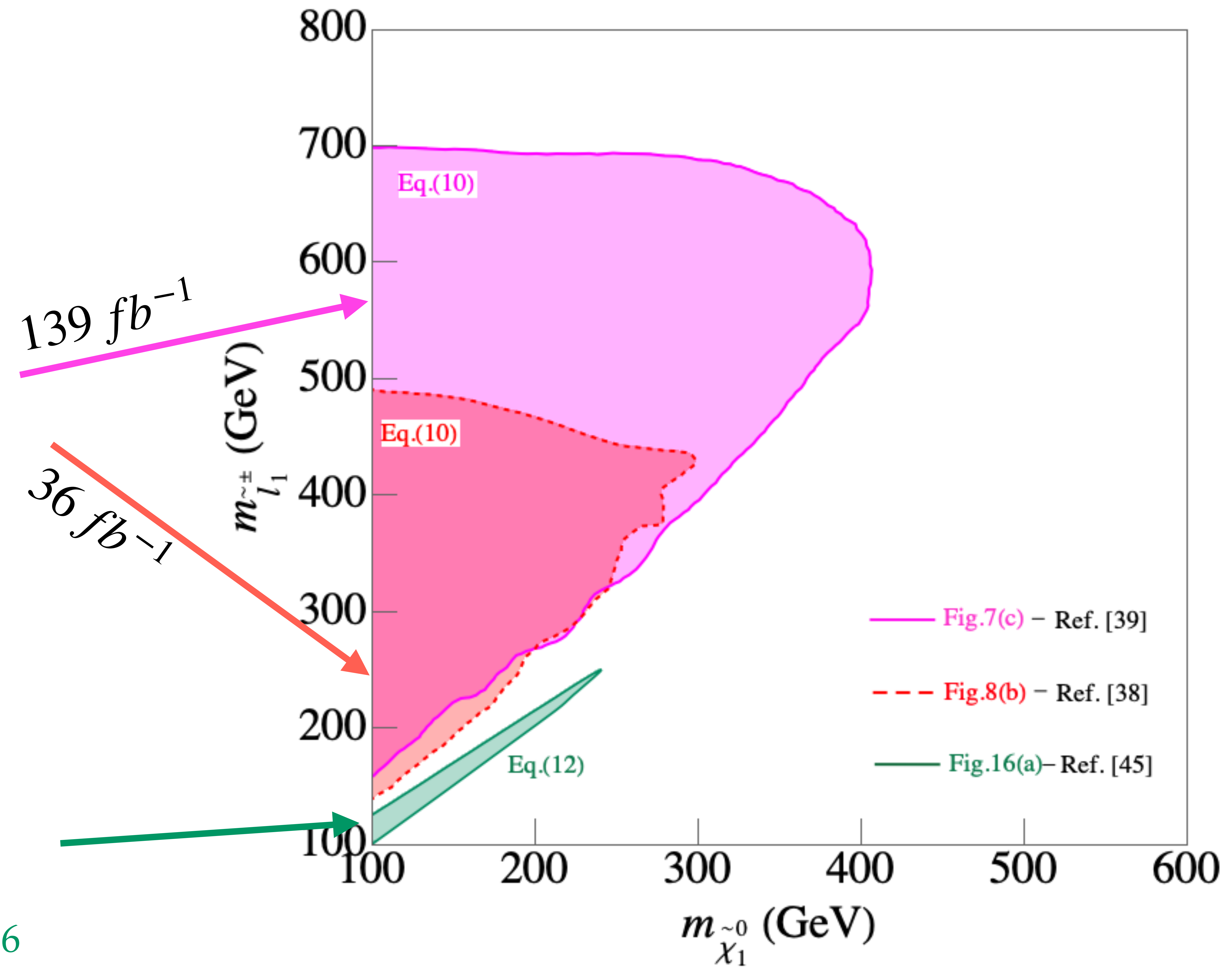
# Searches at the LHC

- Slepton pair production

ATLAS [1908.08215]

13 TeV, 139 $fb^{-1}$





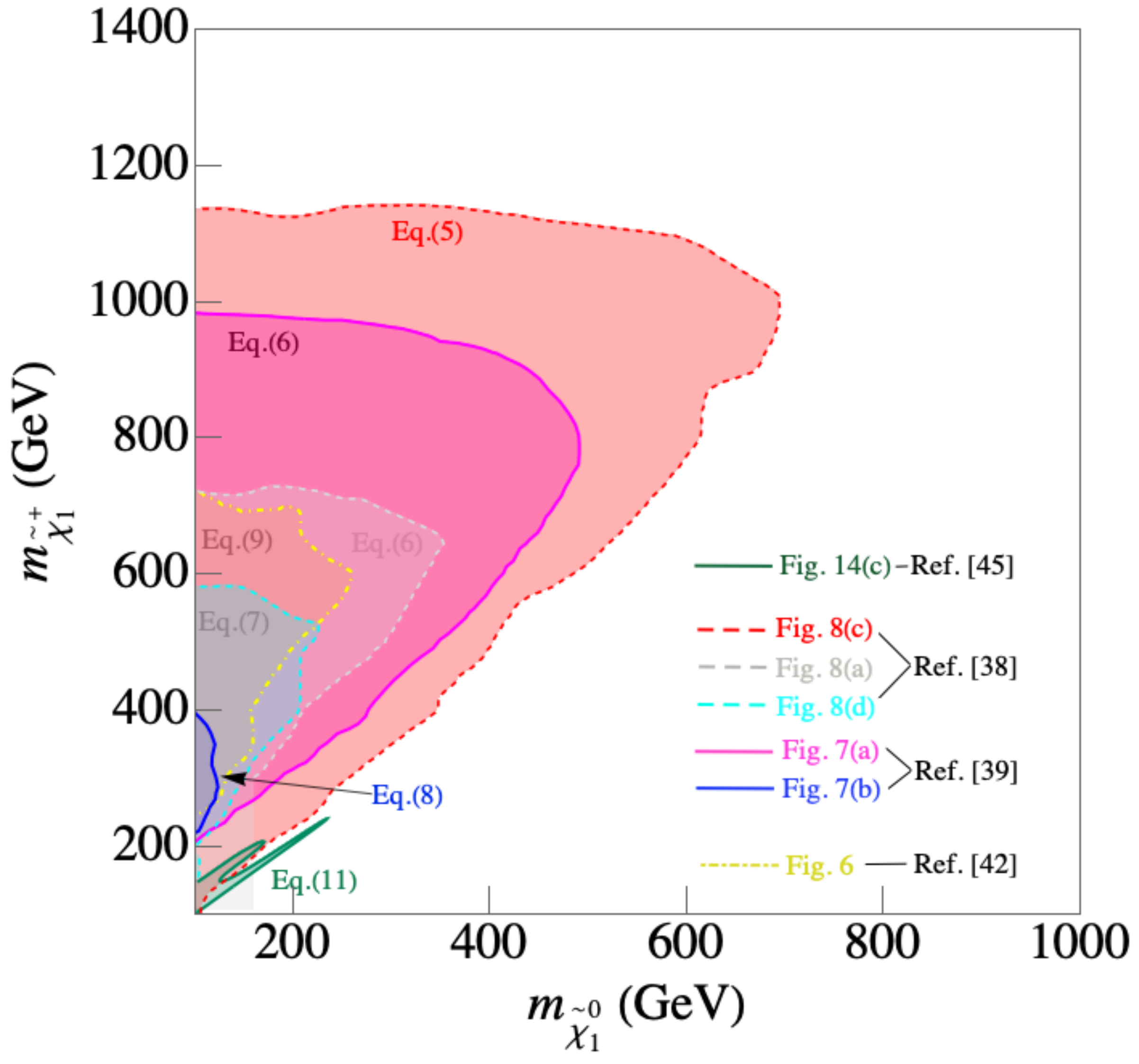
**COMPRESSED**

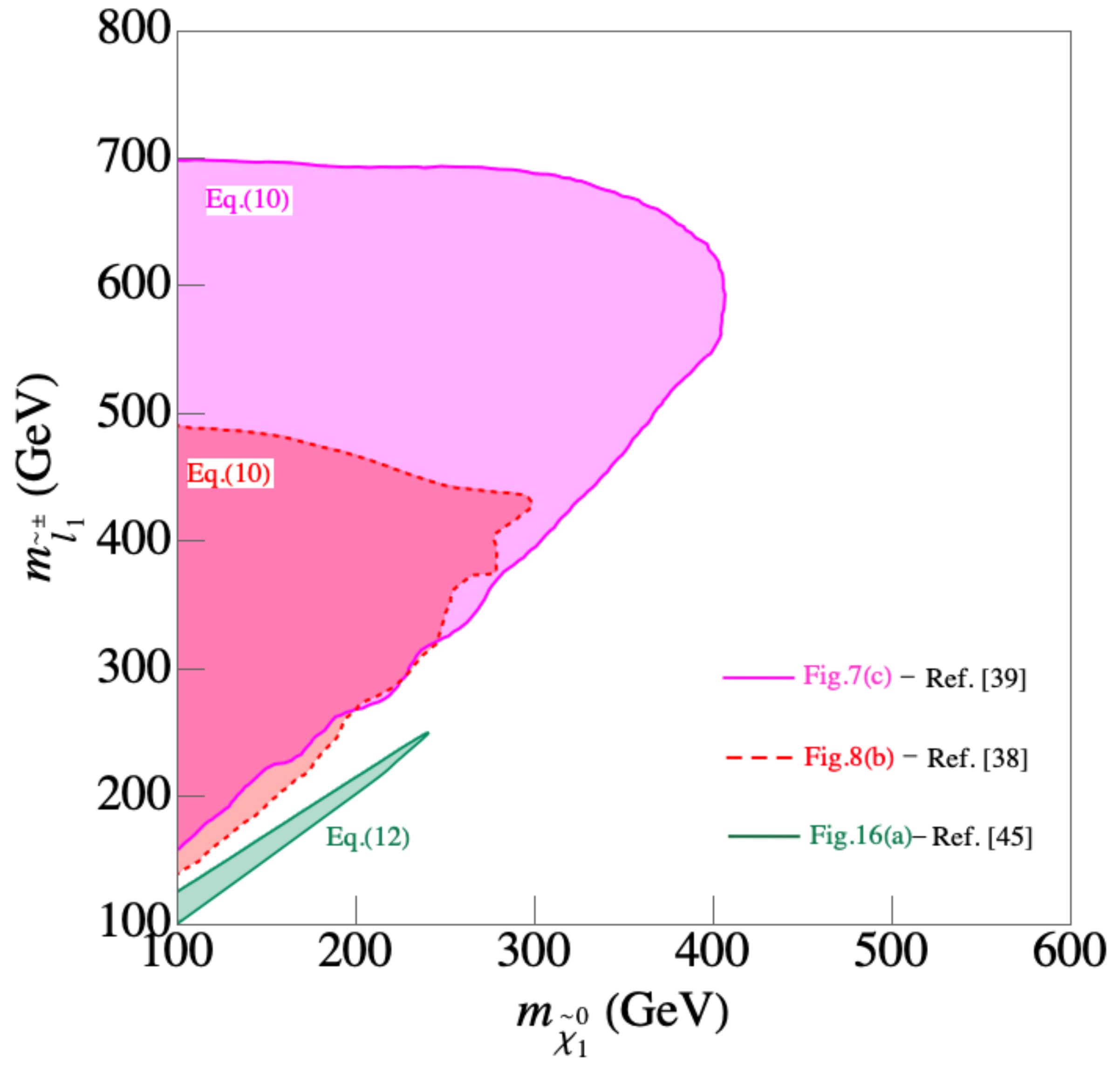
ATLAS 1911.12606

Proper recasting is important → **checkMATE**

# Recasting with CM

Drees, Dreiner, Schmeier, Tattersall, Kim ‘13
Kim, Schmeier, Tattersall, Rolbiecki ‘15
Dercks, Desai, Kim, Rolbiecki, Tattersall ‘16

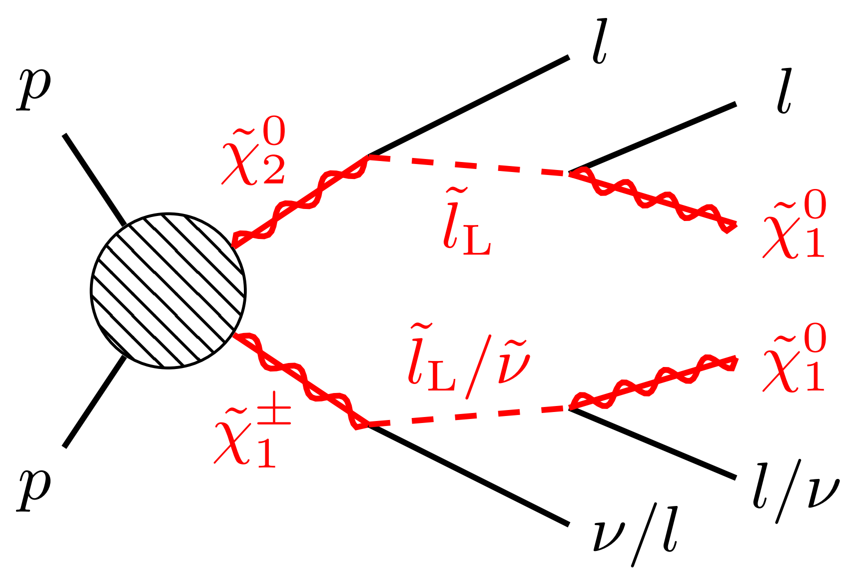




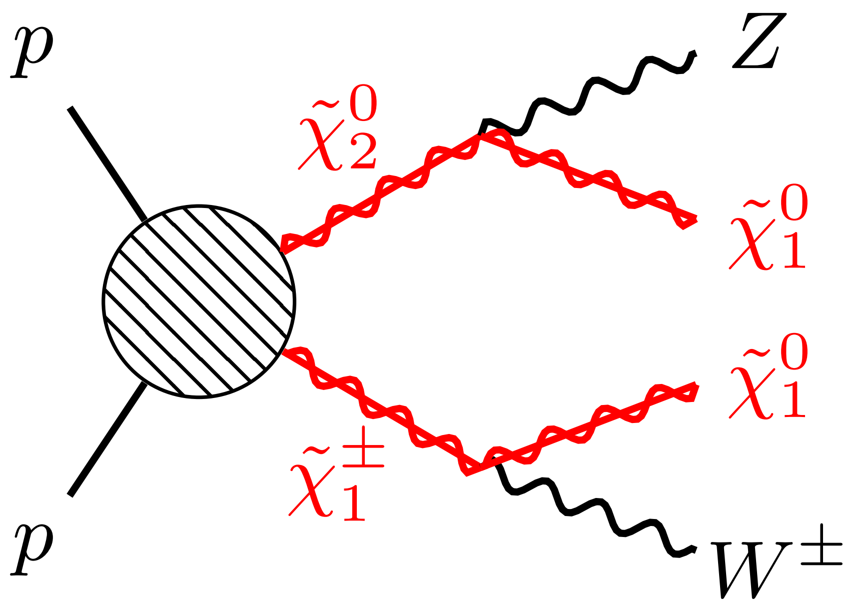
| Show in the color | CheckMATE-implementation |
|---|---|
| Red dashed | ✓ |
| cyan dashed | ✓ |
| Gray dashed | ✓ |
| Magenta | ✓ |
| Blue | ✓ |
| Green | ✗ |
| Magenta | ✓ |
| Red dashed | ✓ |
| Green | ✗ |

Compressed spectra searches applied directly

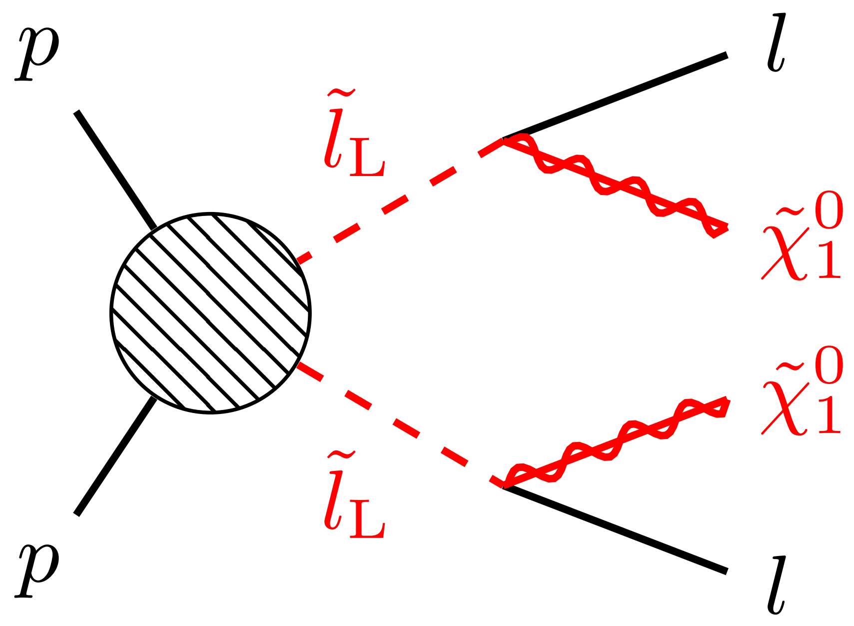
- ATLAS [1803.02762]



- ATLAS [1803.02762]

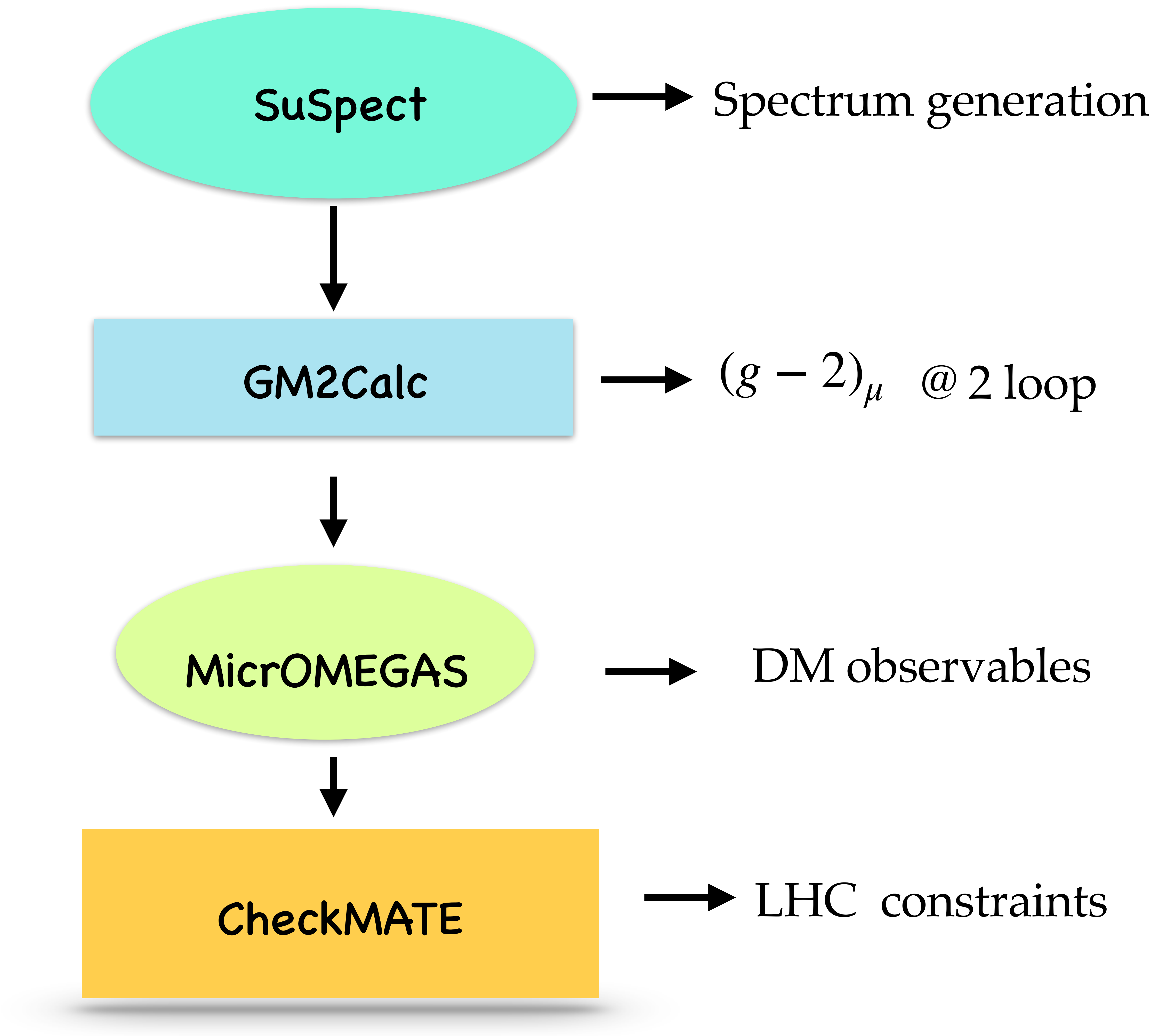


- ATLAS [1908.08215]



Most relevant in our case

# Analysis flow



SuSpect → Spectrum generation

GM2Calc → $(g-2)_\mu$ @ 2 loop

MicrOMEGAS → DM observables

CheckMATE → LHC constraints

- $\Delta a_\mu = (28.02 \pm 7.37) \times 10^{-10}$
- Anticipated future bound

  $\Delta a_\mu^{fut} = (28.02 \pm 5.2) \times 10^{-10}$
- $\Omega_{CDM}h^2 = 0.120 \pm 0.001$
- Direct detection SI bounds from XENON1T

# Parameter Scanning

## Chargino co-annihilation region:

$$100\ \text{GeV} \leq M_1 \leq 1\ \text{TeV}\ , \quad M_1 \leq M_2 \leq 1.1 M_1\ ,$$
$$1.1 M_1 \leq \mu \leq 10 M_1, \quad 5 \leq \tan\beta \leq 60,$$
$$100\ \text{GeV} \leq m_{\tilde{l}_L} \leq 1\ \text{TeV}, \quad m_{\tilde{l}_R} = m_{\tilde{l}_L}\ .$$

Bino-wino co-annihilation

## Slepton co-annihilation region:

Case-L: SU(2) doublet

$$100\ \text{GeV} \leq M_1 \leq 1\ \text{TeV}\ , \quad M_1 \leq M_2 \leq 10 M_1\ ,$$
$$1.1 M_1 \leq \mu \leq 10 M_1, \quad 5 \leq \tan\beta \leq 60,$$
$$M_1\ \text{GeV} \leq m_{\tilde{l}_L} \leq 1.2 M_1, \quad M_1 \leq m_{\tilde{l}_R} \leq 10 M_1\ .$$

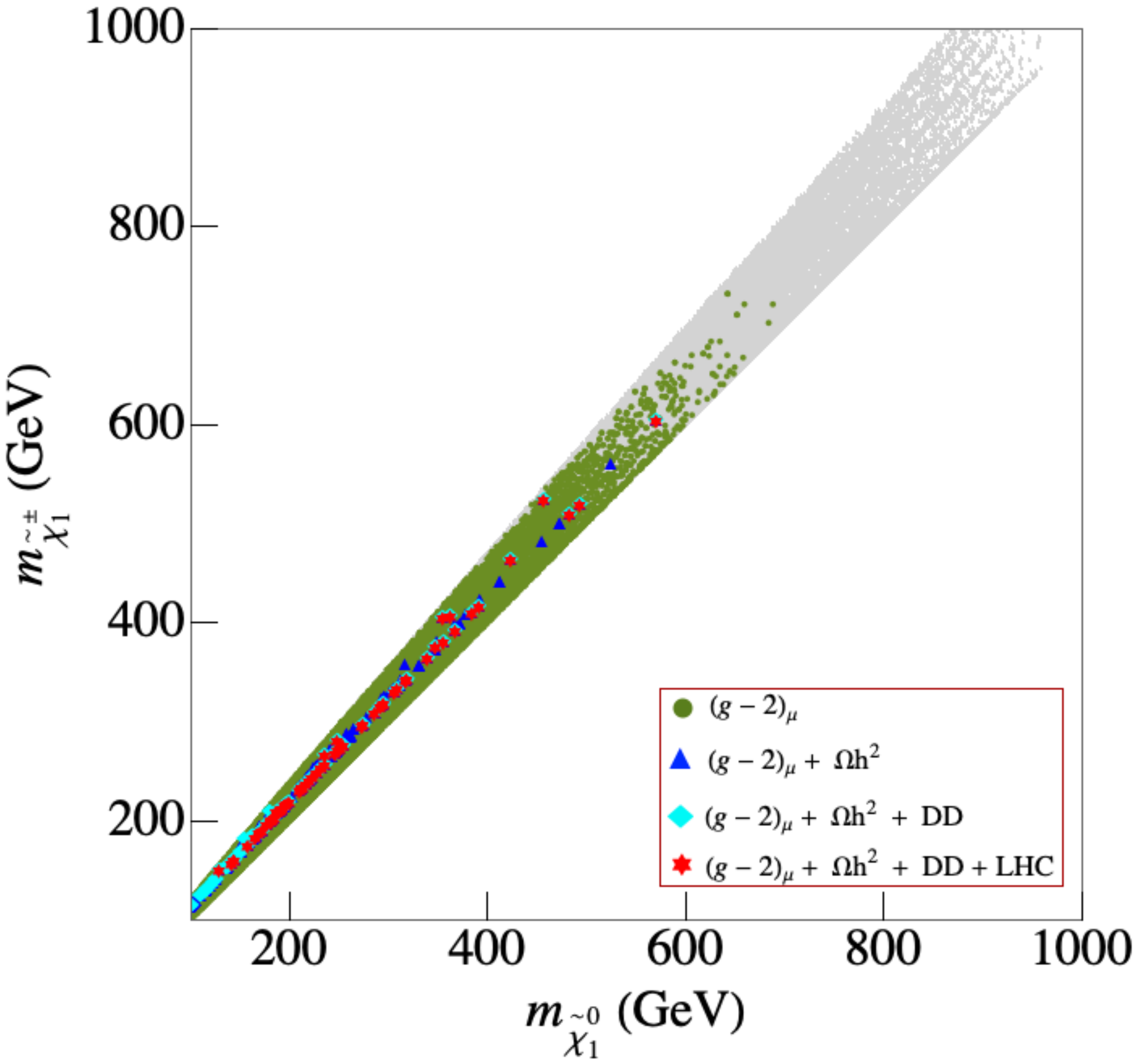
Case-R: SU(2) singlet

$$100\ \text{GeV} \leq M_1 \leq 1\ \text{TeV}\ , \quad M_1 \leq M_2 \leq 10 M_1\ ,$$
$$1.1 M_1 \leq \mu \leq 10 M_1, \quad 5 \leq \tan\beta \leq 60,$$
$$M_1\ \text{GeV} \leq m_{\tilde{l}_R} \leq 1.2 M_1, \quad M_1 \leq m_{\tilde{l}_L} \leq 10 M_1\ .$$

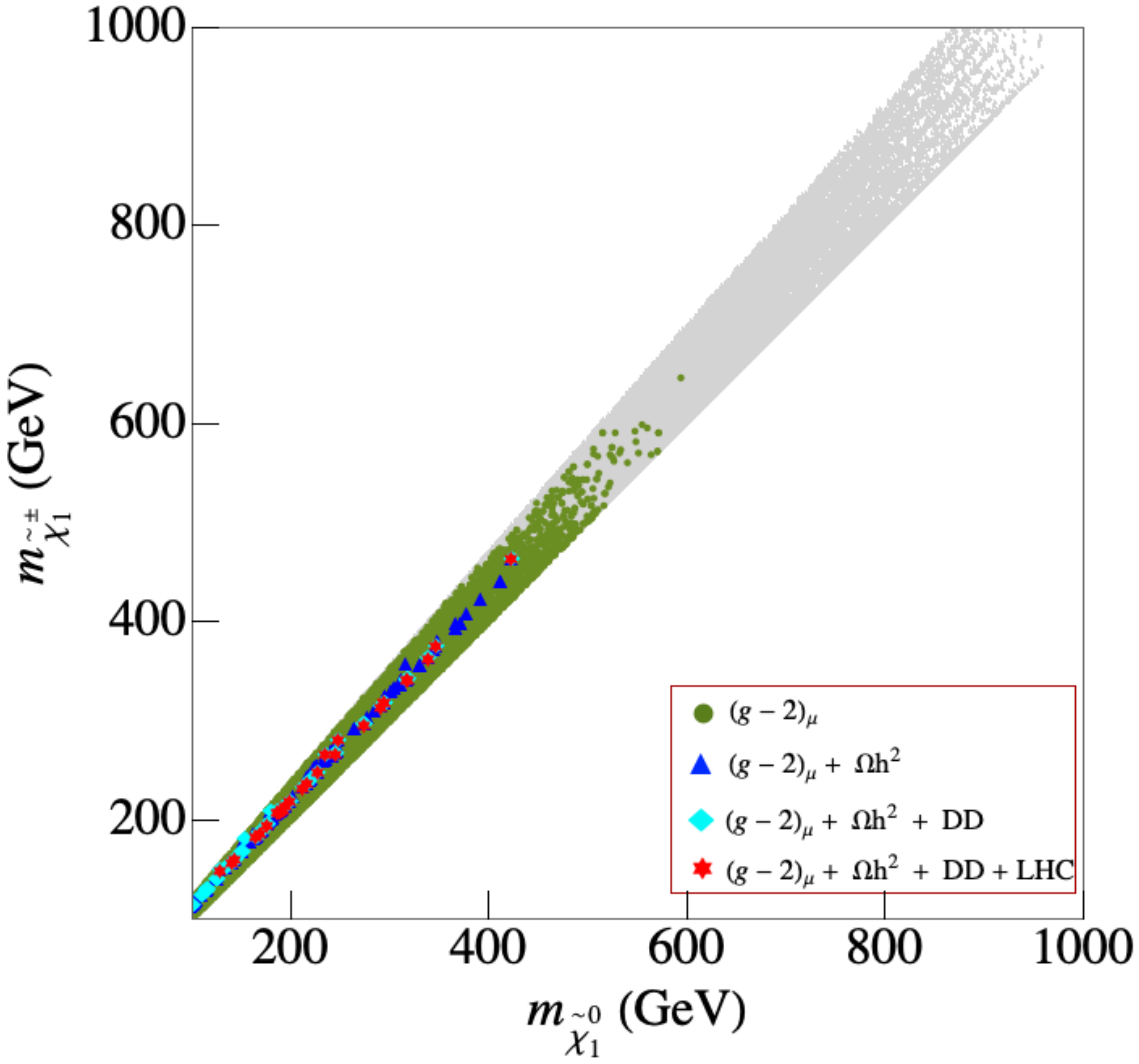
MC, S.Heinemeyer, I.Saha 2006.15157

# Chargino Co-annihilation

Current $(g-2)_\mu$ limit

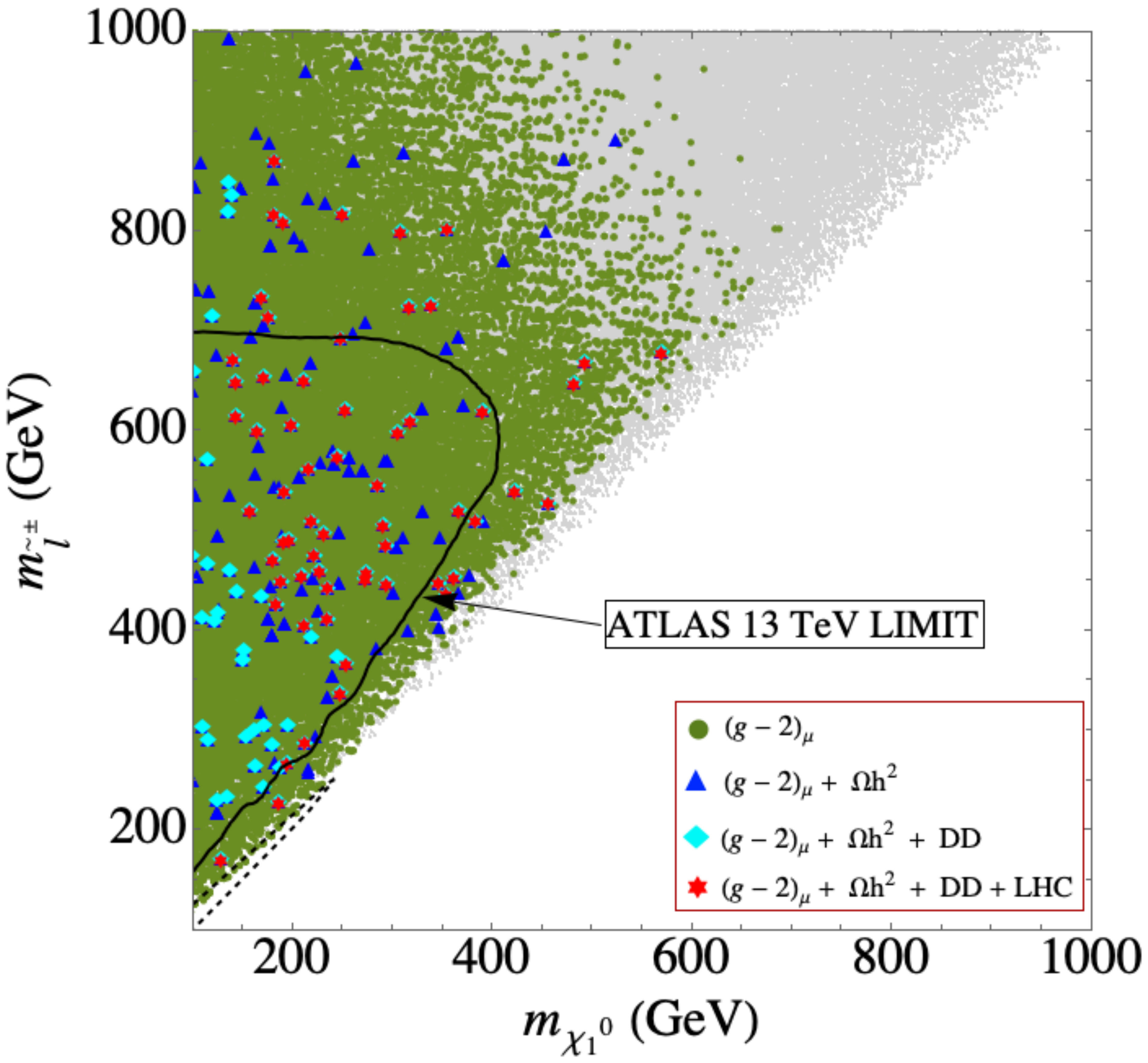


Anticipated future $(g-2)_\mu$ limit



Upper and lower bounds from $(g-2)_\mu$ and LHC searches ( for compressed spectrum)

# Results in the $m_{\tilde{\chi}_1^0} - m_{\tilde{l}_1}$ plane



Current $(g-2)_\mu$ limit

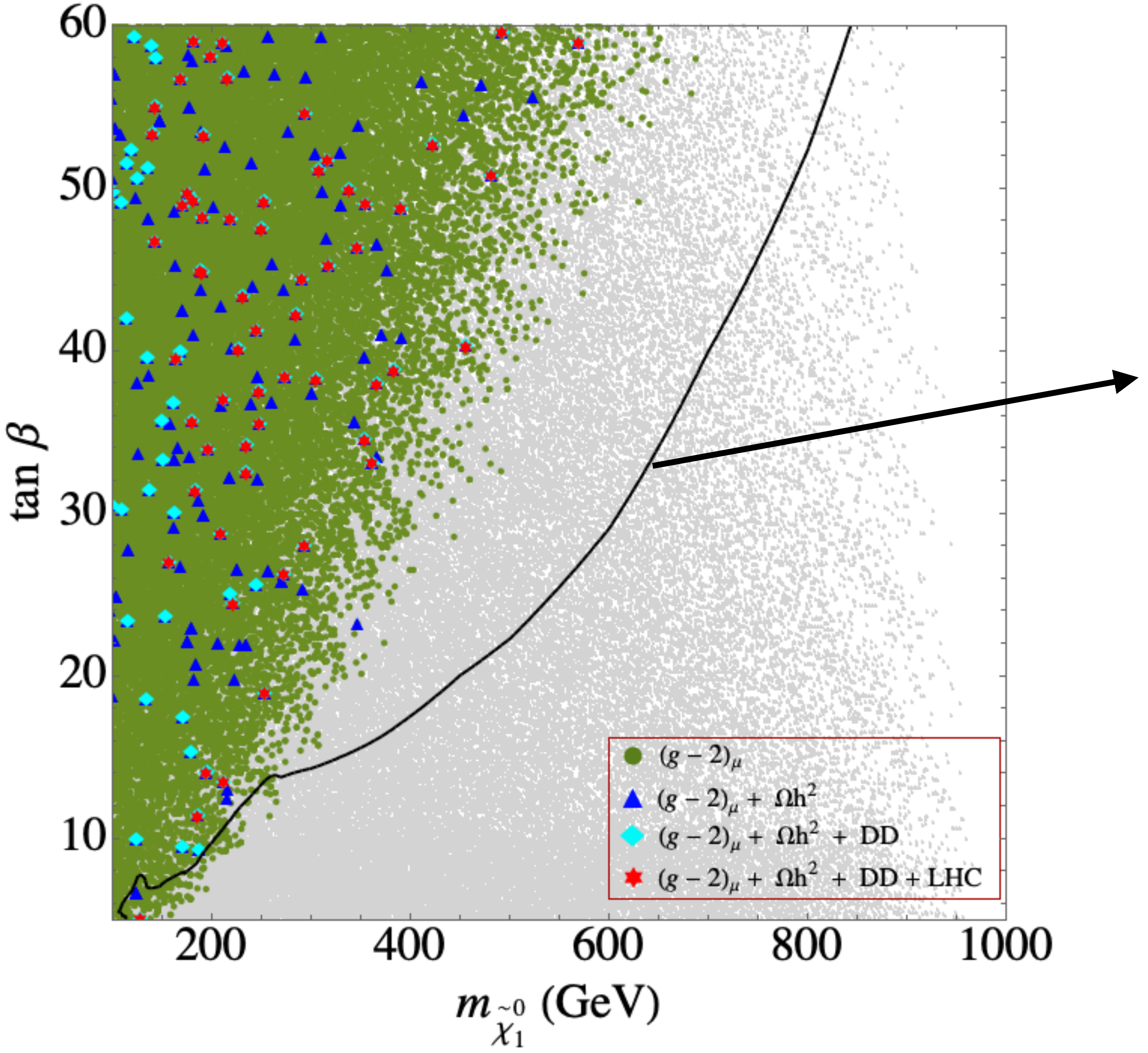
Slepton-pair production →( *2l* + missing $E_T$ ) provides important search channel ....

R-sleptons heavy, Considerable BR for $\tilde{e}_L(\tilde{\mu}_L) \rightarrow \tilde{\chi}_1^{\pm}\nu_e(\nu_\mu)$ → Less no. of signal leptons.

# Possibility of A-pole annihilation

$$a_\mu \sim \frac{\tan\beta}{m_{EW}^2}$$

Current $(g-2)_\mu$ limit



$$m_{\tilde{\chi}_1^0} = \frac{M_A}{2}$$

$M_h^{125}(\tilde{\chi})$ Benchmark scenario

Bagnaschi et al. ‘18

Black contour : simplified application of $H/A \to \tau^+\tau^-$ → A-pole annihilation strongly constrained

# DM with Low abundance

$$\Omega_{CDM}h^2 \leq 0.122$$

## Wino LSP

$$\begin{aligned} 100\ \text{GeV} \leq M_2 \leq 1.5\ \text{TeV}\ , \quad & 1.1 M_2 \leq M_1 \leq 10 M_2\ , \\ 1.1 M_2 \leq \mu \leq 10 M_2, \quad & 5 \leq \tan\beta \leq 60, \\ 100\ \text{GeV} \leq m_{\tilde{l}_L}, m_{\tilde{l}_R} & \leq 2\ \text{TeV}\ . \end{aligned}$$

$SU(2)_L$ triplet

Under-abundant upto ~ 3 TeV

Compressed spectra with $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_1^\pm}$

## Higgsino LSP

$$\begin{aligned} 100\ \text{GeV} \leq \mu \leq 1.2\ \text{TeV}\ , \quad & 1.1 \mu \leq M_1 \leq 10 \mu\ , \\ 1.1 \mu \leq M_2 \leq 10 \mu, \quad & 5 \leq \tan\beta \leq 60, \\ 100\ \text{GeV} \leq m_{\tilde{l}_L}, m_{\tilde{l}_R} & \leq 2\ \text{TeV}\ . \end{aligned}$$

$SU(2)_L$ doublet

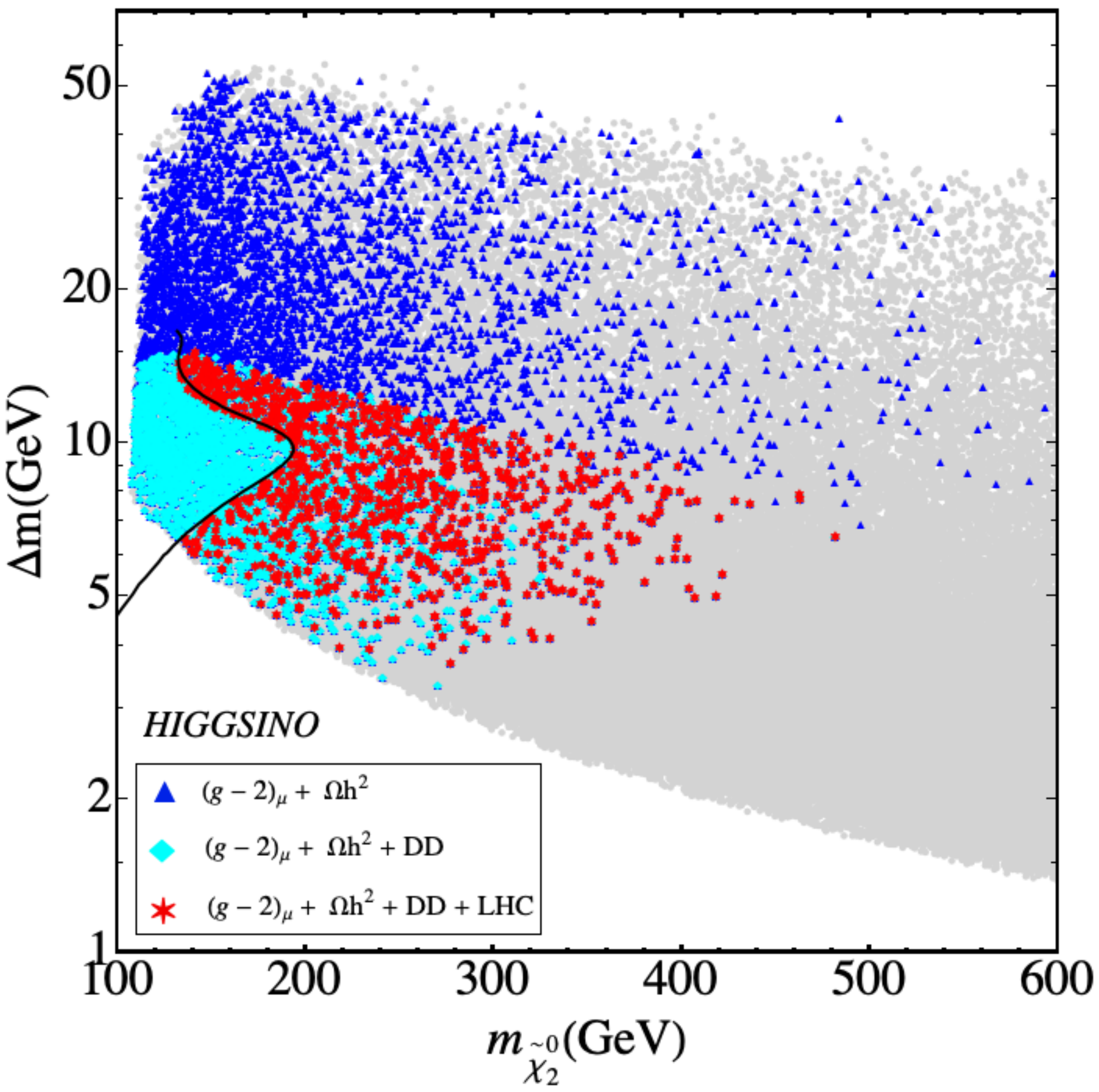
Under-abundant upto ~ 1 TeV

Compressed spectra with $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_2^0}$

2103.XXXXX , WITH SVEN HEINEMEYER AND IPSITA SAHA

# Higgsino LSP

Current $(g-2)_\mu$ limit

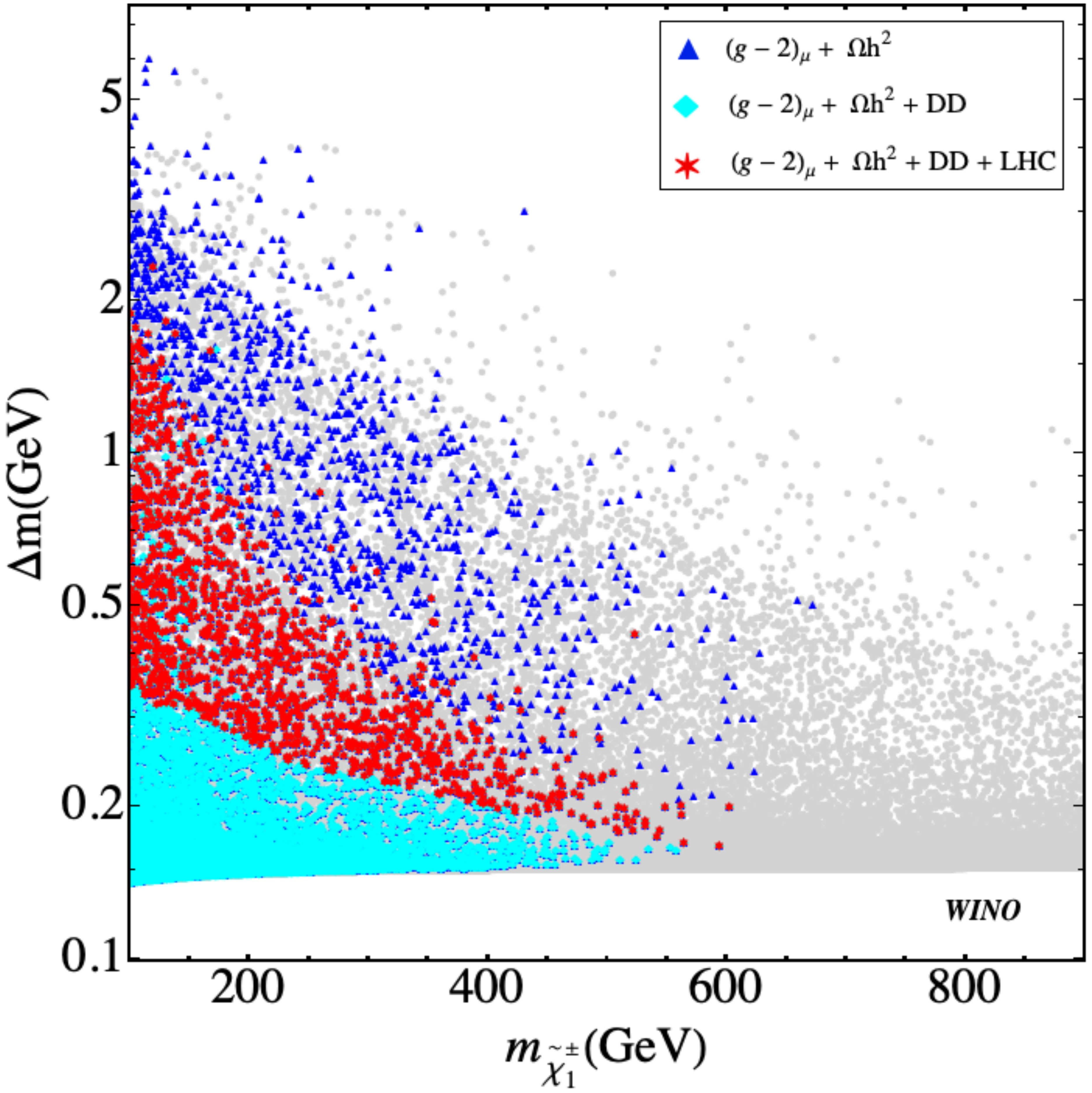


- Compressed spectra searches most important.
- Slepton pair production searches also relevant
- $\Delta m \sim \mathcal{O}(10)$ GeV → Disappearing track searches not sensitive

$$c\tau \simeq 0.7\ \mathrm{cm} \times \left[ \left( \frac{\Delta m_+}{340\,\mathrm{MeV}} \right)^3 \sqrt{1 - \frac{m_\pi^2}{\Delta m_+^2}} \right]^{-1}$$

# Wino LSP

Current $(g-2)_\mu$ limit



High $\Delta m$ restricted by DD

Low $\Delta m$ restricted by LHC

- Tree level splitting from $\tilde{h}$ mixing

$$\boxed{\simeq \frac{M_W^4 (\sin 2\beta)^2 \tan^2 \theta_w}{(M_1 - M_2)\mu^2}}$$

- Coupling for DD

$$\boxed{c_{h\tilde{\chi}_1^0\tilde{\chi}_1^0} \simeq \frac{M_W}{M_2^2 - \mu^2}(M_2 + \mu \sin 2\beta),}$$

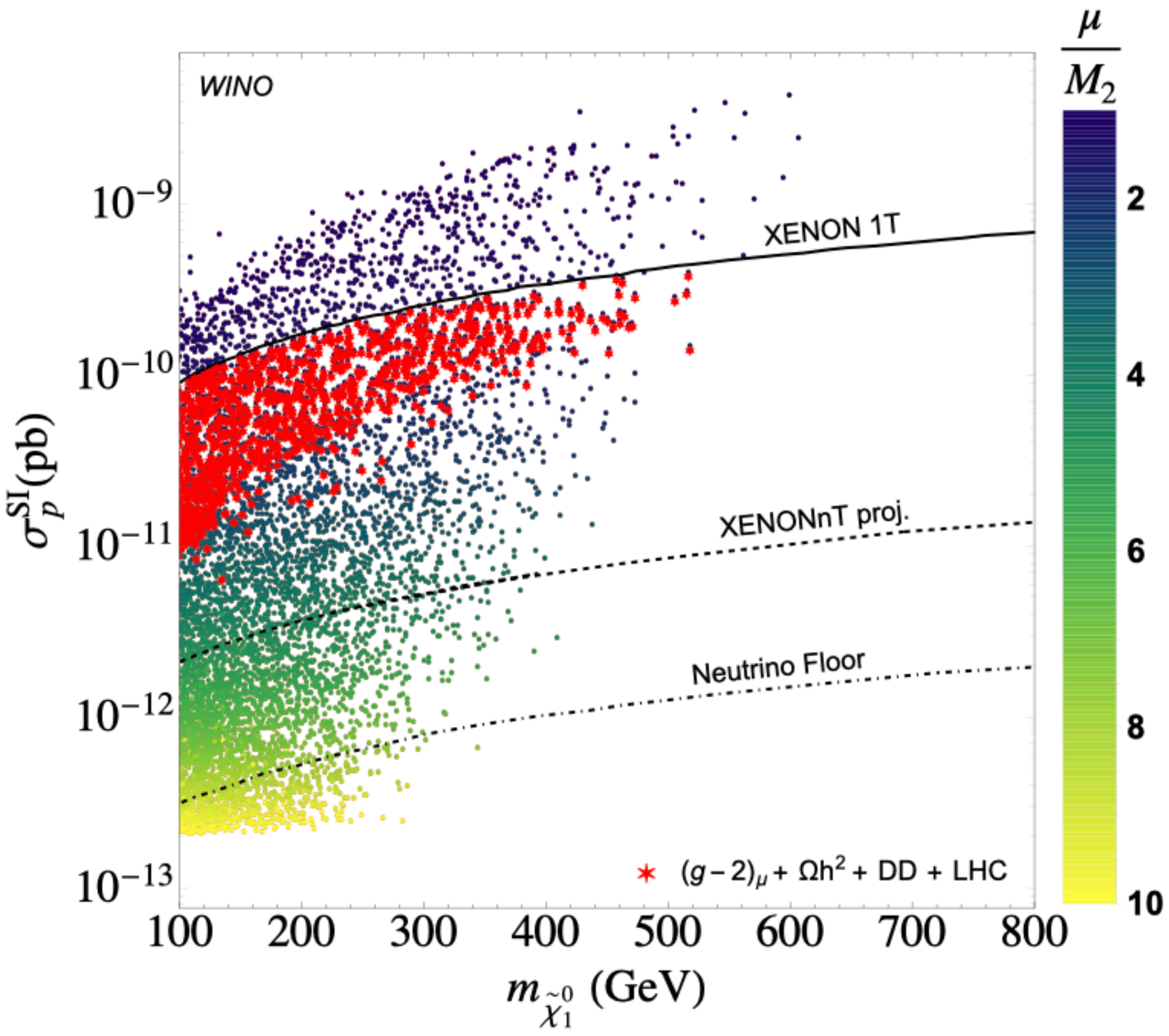
Ibe, Matsumoto, Sato '13

- Disappearing track searches $\tilde{\chi}_1^\pm \to \pi^\pm \tilde{\chi}_1^0$

CMS-EXO-19-010

# Wino LSP : Direct detection

Current $(g-2)_\mu$ limit

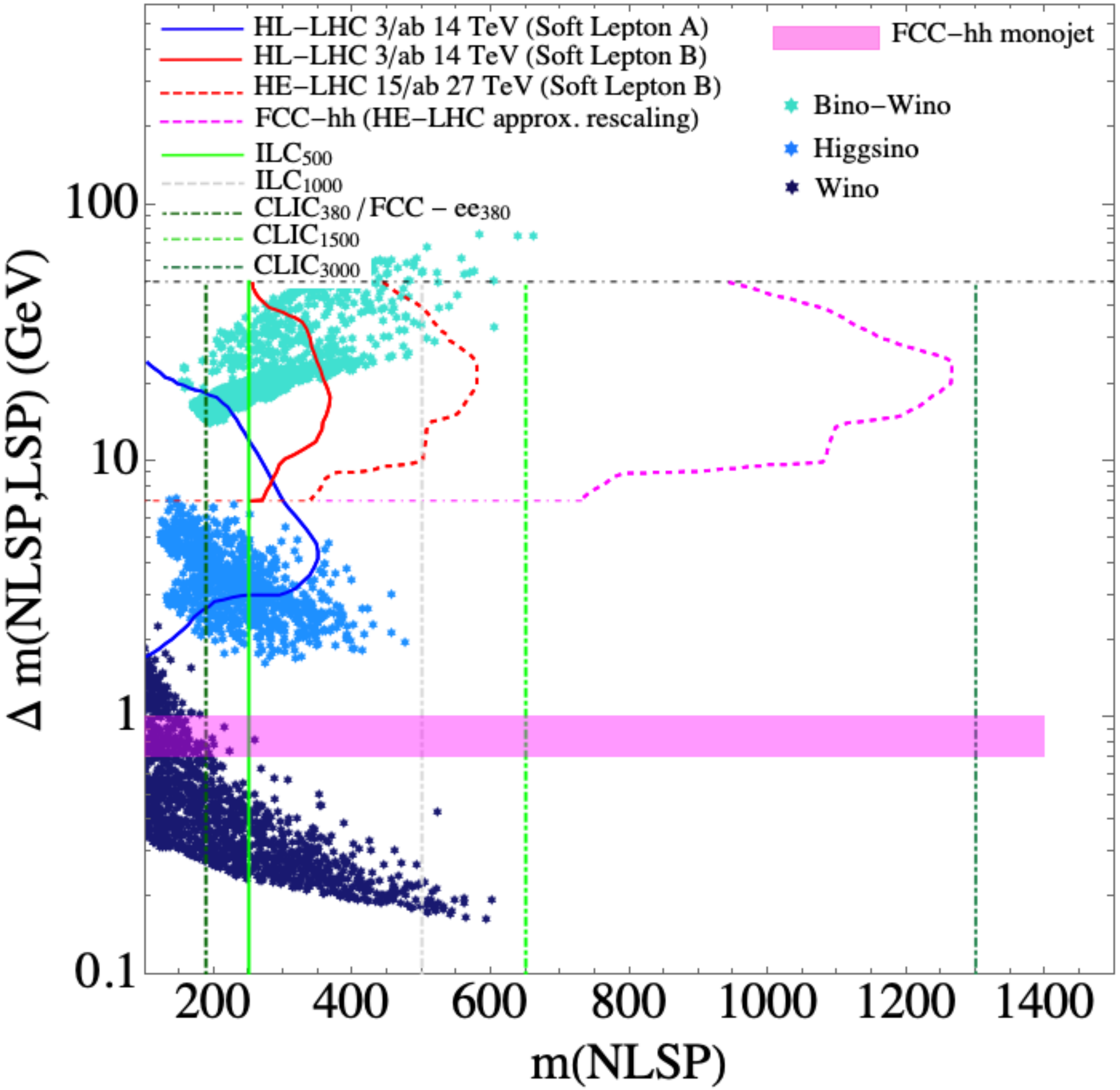


- DD coupling

$$c_{h\tilde{\chi}_1^0\tilde{\chi}_1^0} \simeq \frac{M_W}{M_2^2-\mu^2}(M_2+\mu\sin 2\beta),$$

- All allowed points to be checked by XENONnT

# Future prospects



Breggren ‘ 20

# Conclusions

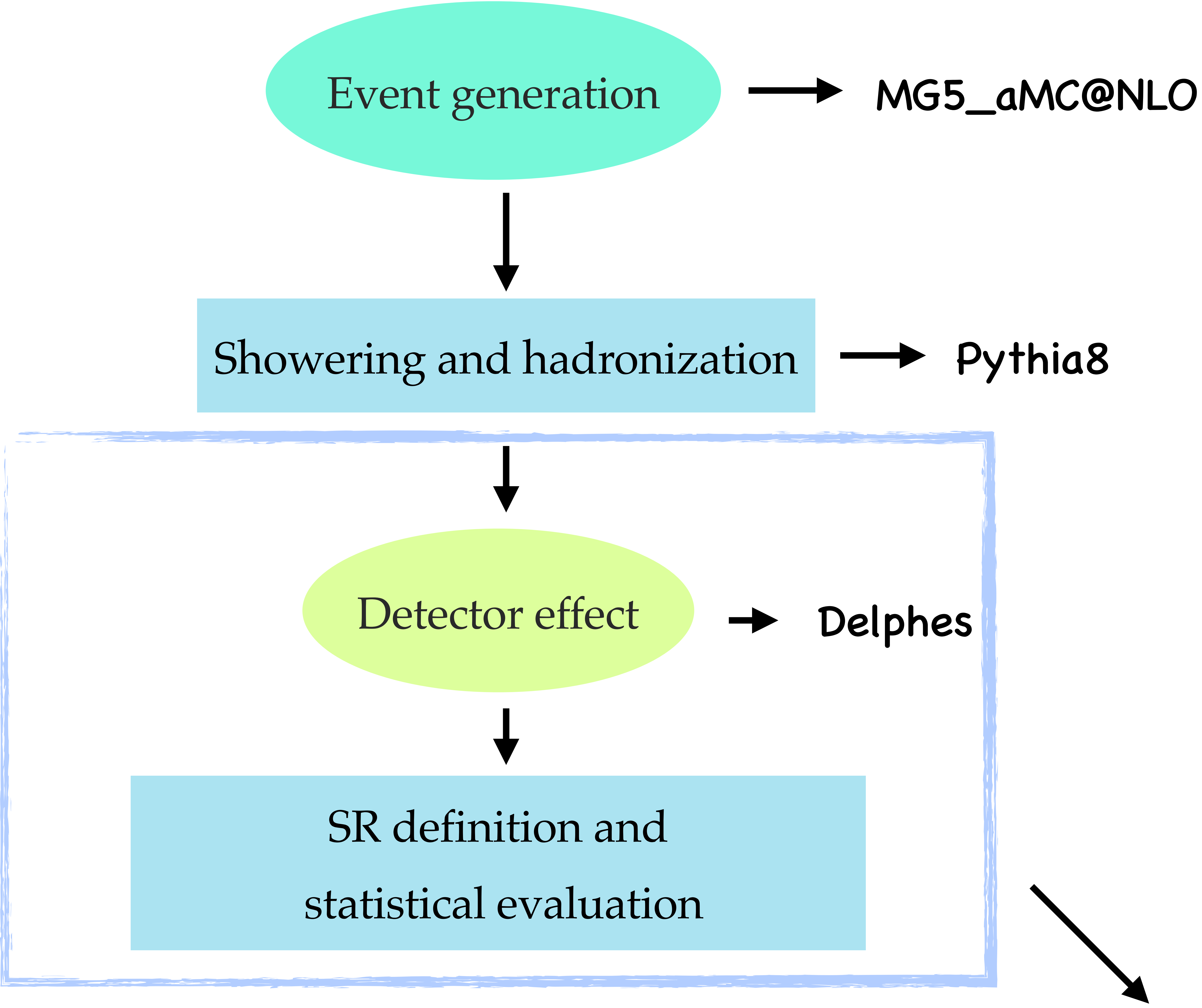
- It is possible to constrain the EW MSSM with the help of indirect constraints along with the direct collider limits.
- DM and muon (g-2) constraints put effective upper limit on EW SUSY masses.
- LHC limits restrict the mass ranges from below.
- Proper recasting of ATLAS/CMS analyses important !
- Future linear collider searches will be conclusive.
- New experimental results for $(g-2)_\mu$ from Fermilab, J-PARC …. STAY TUNED!!!

# THANK YOU!

# BACKUP

# Recasting with CM

Drees, Dreiner, Schmeier, Tattersall, Kim ‘13
Kim, Schmeier, Tattersall, Rolbiecki ‘15
Dercks, Desai, Kim, Rolbiecki, Tattersall ‘16



Event generation → MG5_aMC@NLO

Showering and hadronization → Pythia8

Detector effect → Delphes

SR definition and statistical evaluation

New analysis implementation

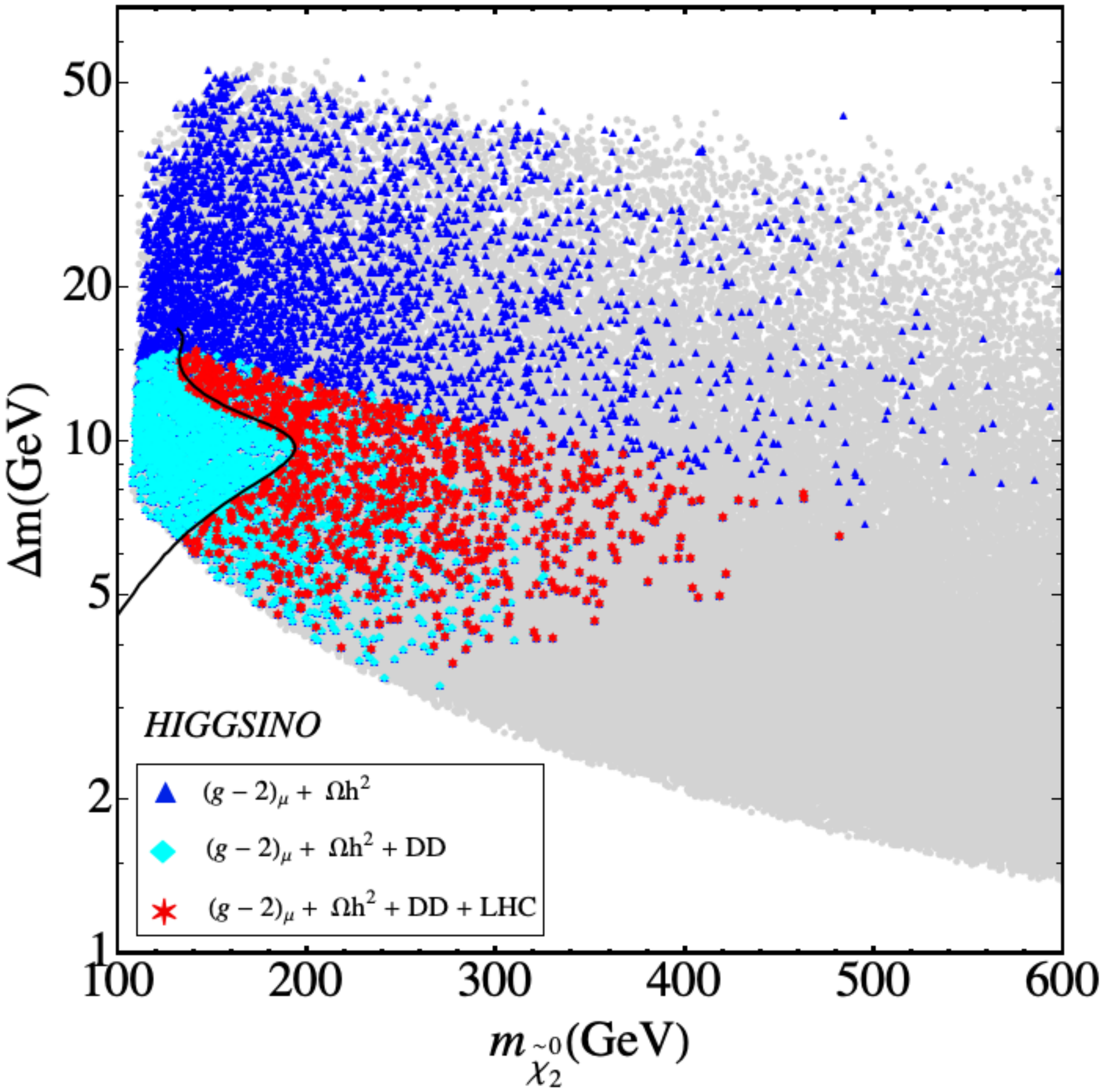
CheckMATE → Experimental Cutflow reproduced

## Model testing

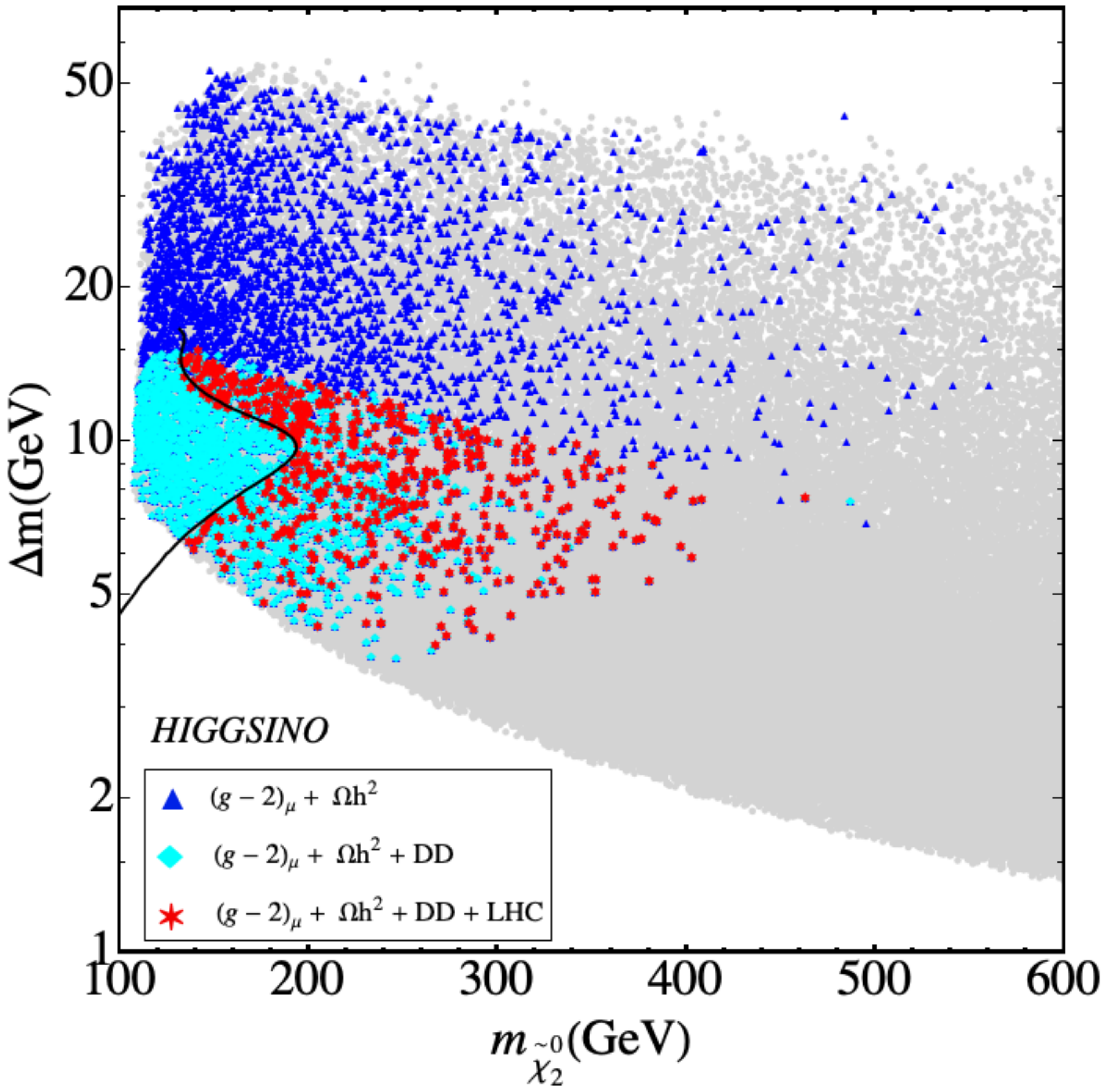
- Each parameter point is tested against newly implemented analyses
- Signal events calculated for each SR
- Evaluation of $r = \dfrac{S - 1.96 \times \Delta S}{S^{95}_{exp}}$
- For the best SR, $r > 1 \longrightarrow$ excluded!

# Higgsino LSP

Current $(g-2)_\mu$ limit

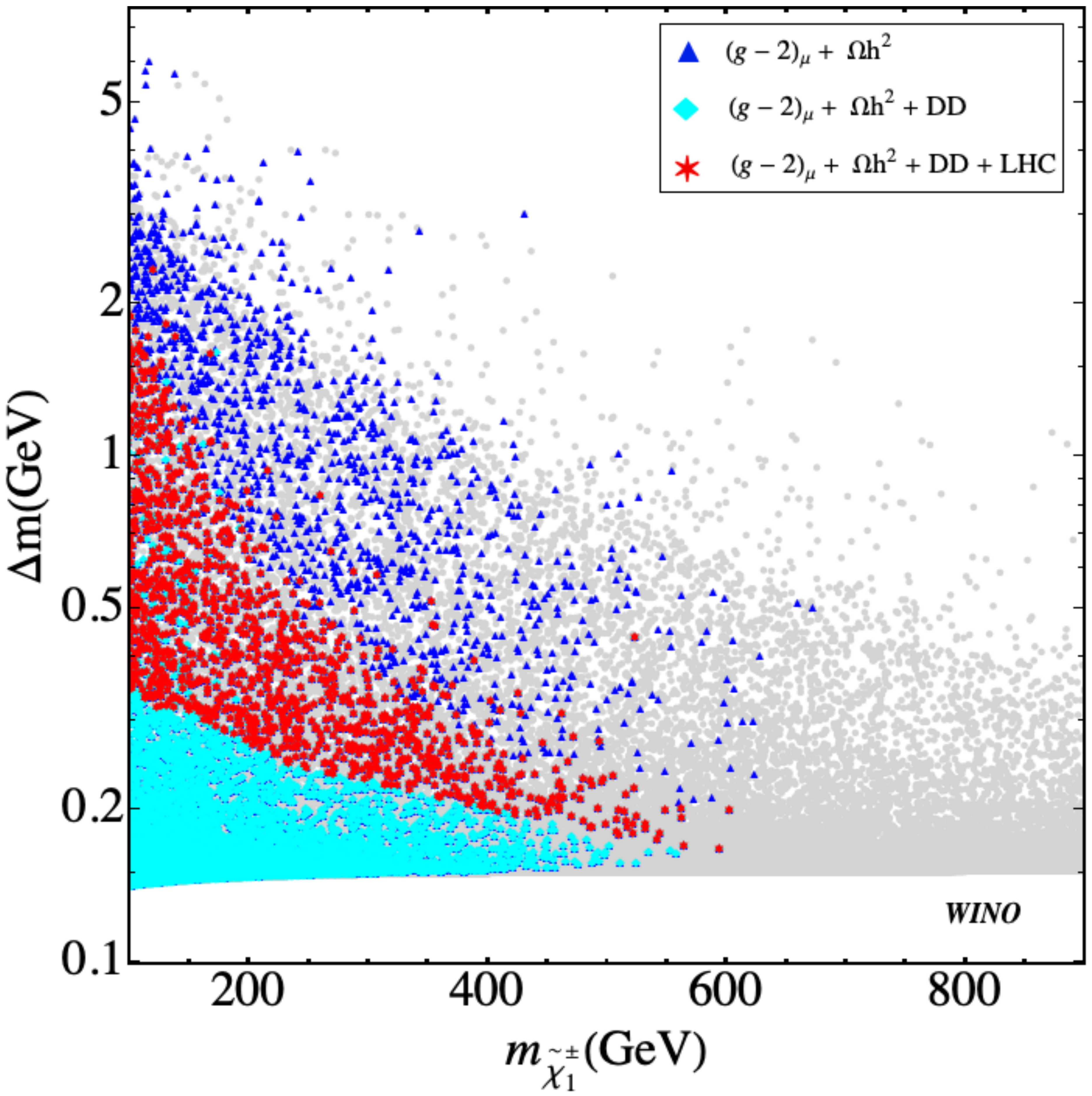


Future $(g-2)_\mu$ limit

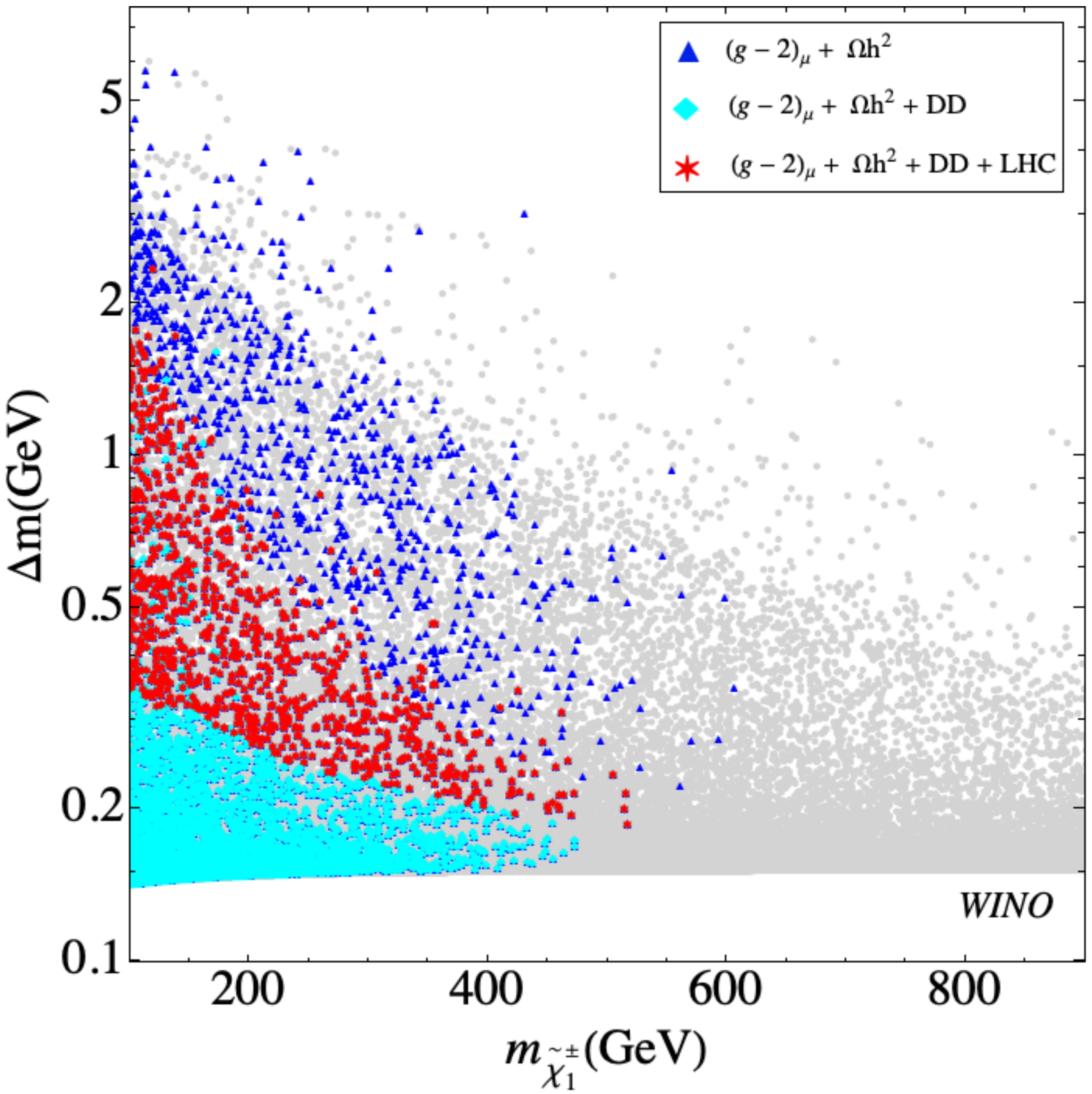


# Wino LSP

Current $(g-2)_\mu$ limit

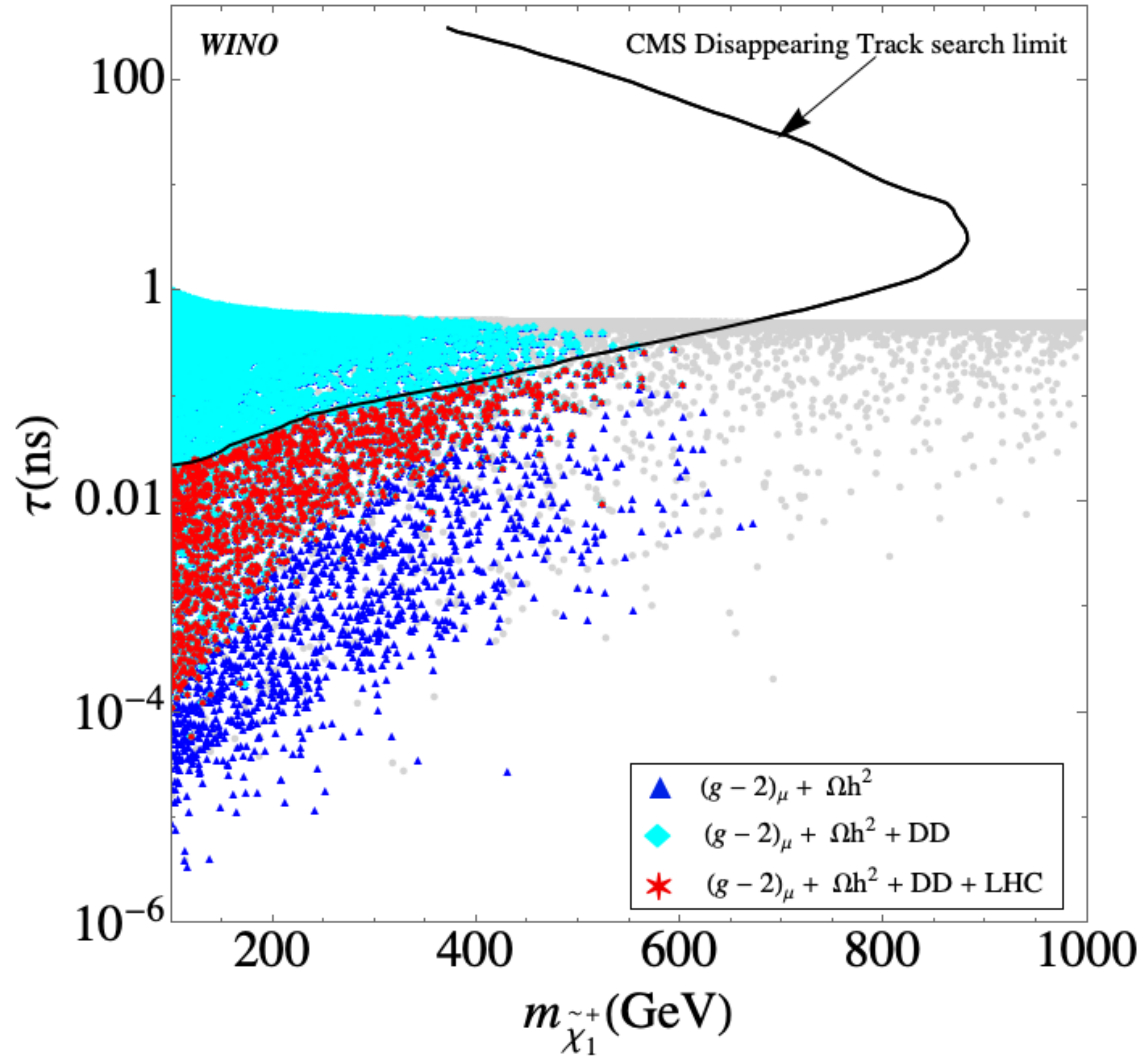


Future $(g-2)_\mu$ limit



# Wino LSP lifetime

Current $(g-2)_\mu$ limit



$$\Gamma(\tilde{\chi}^\pm \to \tilde{\chi}^0 \pi^\pm) = \Gamma(\pi^\pm \to \mu^\pm \nu_\mu) \times \frac{16\delta m^3}{m_\pi m_\mu^2}\left(1 - \frac{m_\pi^2}{\delta m^2}\right)^{1/2}\left(1 - \frac{m_\mu^2}{m_\pi^2}\right)^{-2}$$

$$\Gamma(\tilde{\chi}^\pm \to \tilde{\chi}^0 e^\pm \nu_e) \simeq \frac{2G_F^2}{15\pi^3}\delta m^5.$$

- Disappearing track searches most important.

# MSSM Superpotential

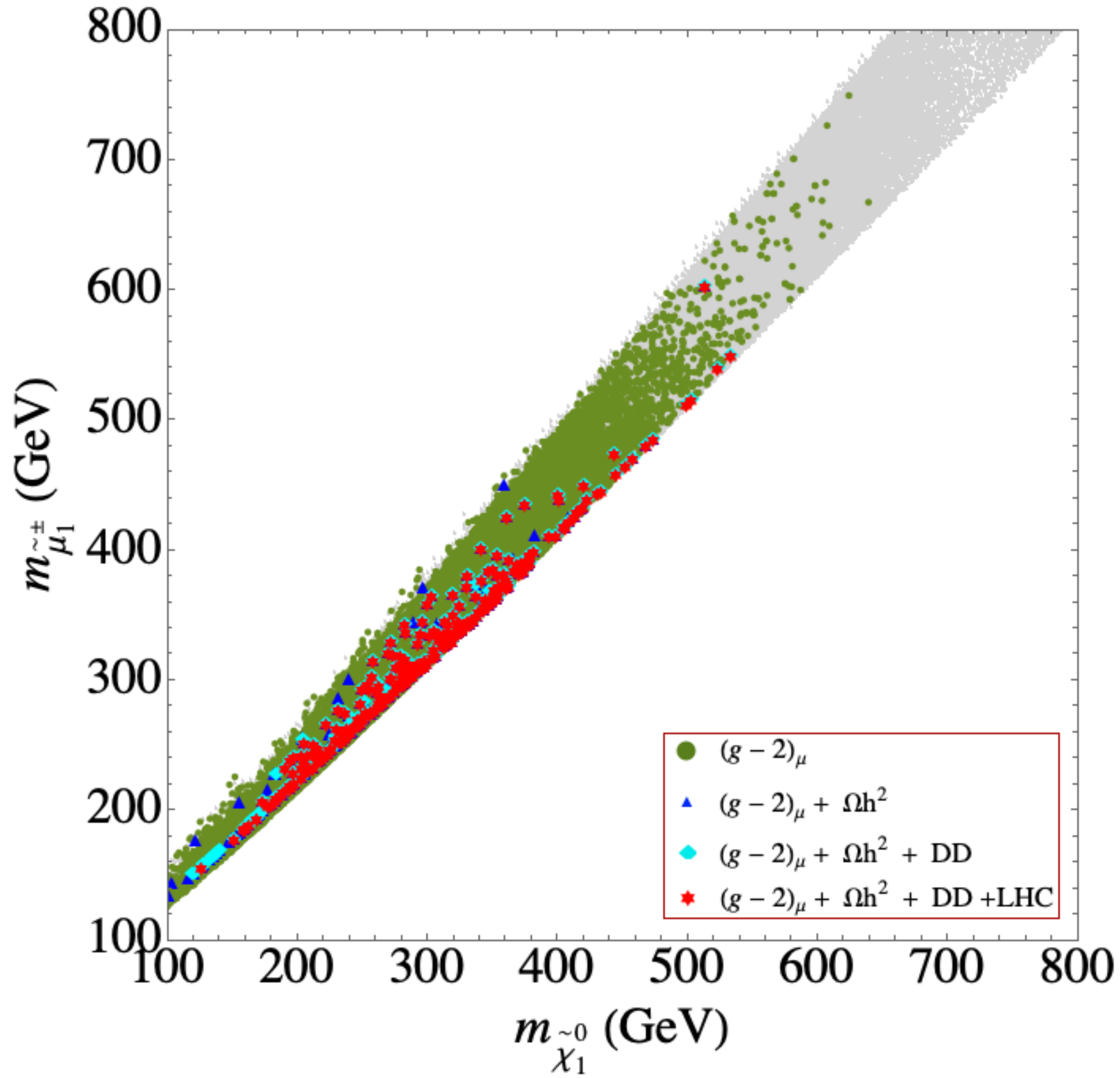
$$W_{\text{MSSM}} = \bar{u} Y_u Q H_u - \bar{d} Y_d Q H_d - \bar{e} Y_e L H_d + \mu H_u H_d$$

## Soft Breaking Terms

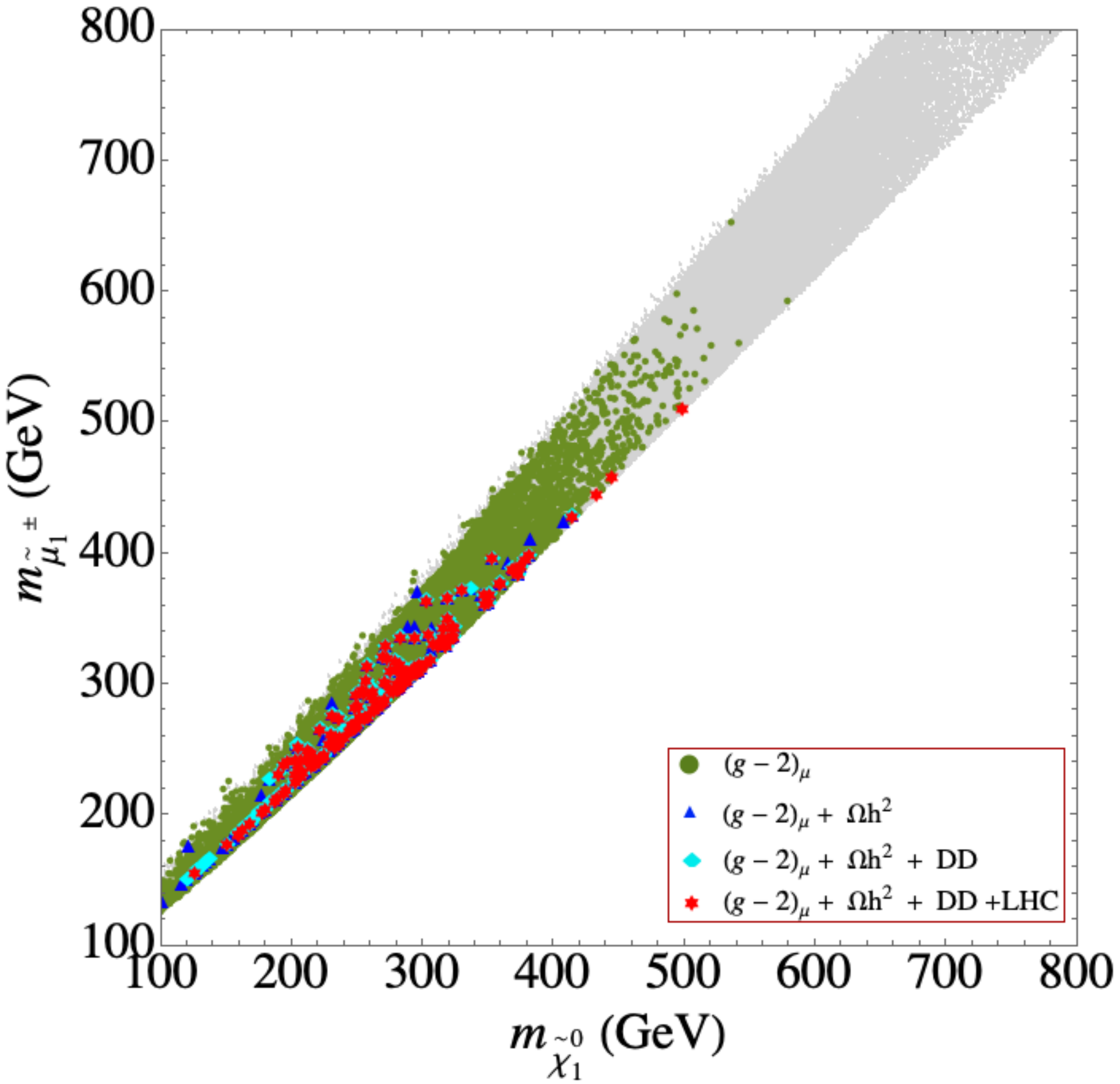
$$\begin{aligned}\mathcal{L}_{\text{soft}}^{\text{MSSM}} = & -\frac{1}{2}\left(M_3 \tilde{g}\tilde{g} + M_2 \tilde{W}\tilde{W} + M_1 \tilde{B}\tilde{B} + c\,.\,c\right) \\ & -\left(\tilde{\bar{u}}\,\mathbf{a_u}\,\tilde{Q}H_u - \tilde{\bar{d}}\,\mathbf{a_d}\,\tilde{Q}H_d - \tilde{\bar{e}}\,\mathbf{a_e}\,\tilde{L}H_d + c\,.\,c\right) \\ & -\tilde{Q}^\dagger \mathbf{m_Q^2}\,\tilde{Q} - \tilde{L}^\dagger\,\mathbf{m_L^2}\,\tilde{L} - \tilde{\bar{u}}\,\mathbf{m_{\bar{u}}^2}\,\tilde{\bar{u}}^\dagger - \tilde{\bar{d}}\,\mathbf{m_{\bar{d}}^2}\,\tilde{\bar{d}}^\dagger - \tilde{\bar{e}}\,\mathbf{m_{\bar{e}}^2}\,\tilde{\bar{e}}^\dagger \\ & - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - \left(b H_u H_d + c\,.\,c\right)\end{aligned}$$

# Slepton Co-annihilation: Case-L

Current $(g-2)_\mu$ limit



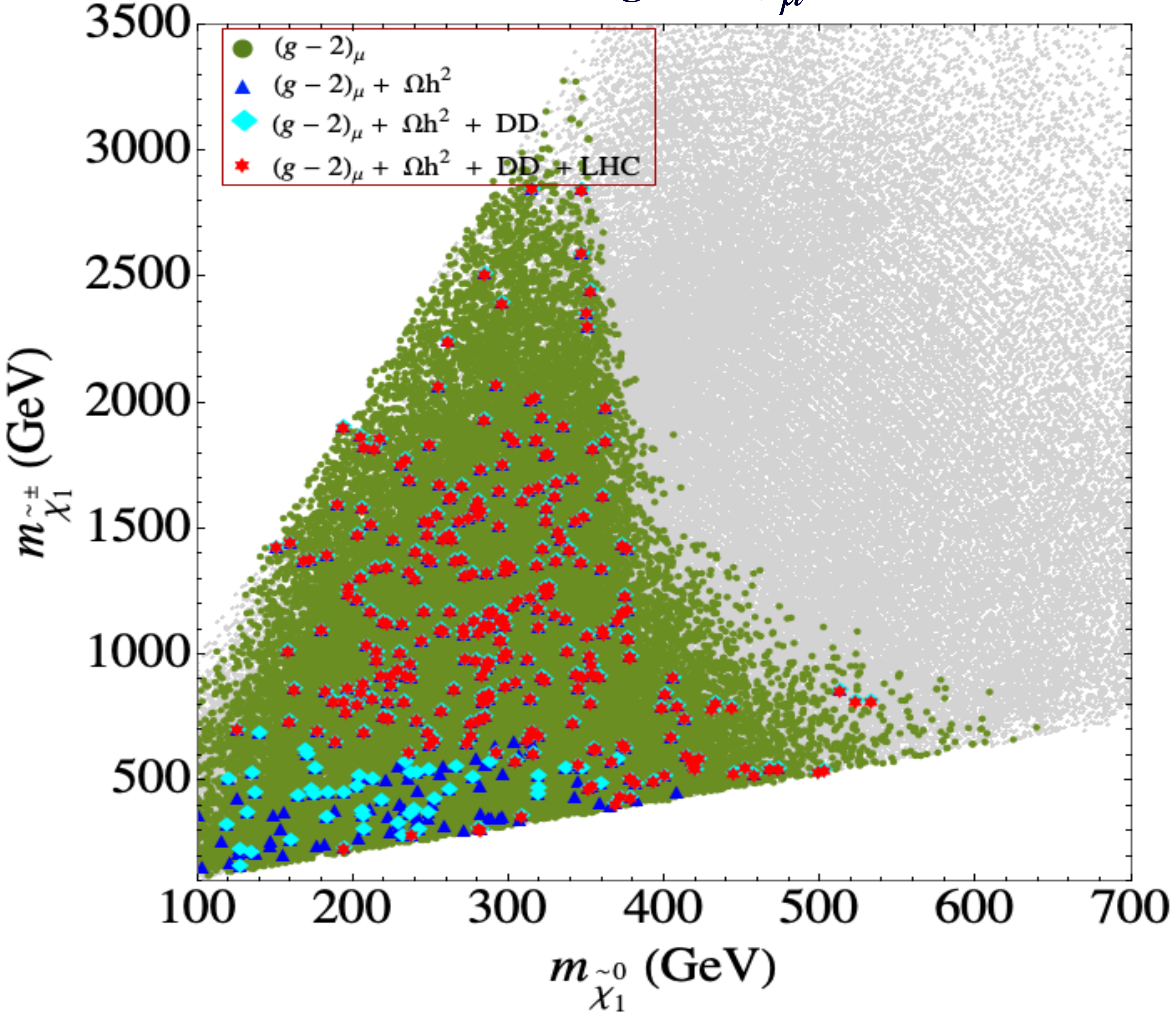
Anticipated future $(g-2)_\mu$ limit

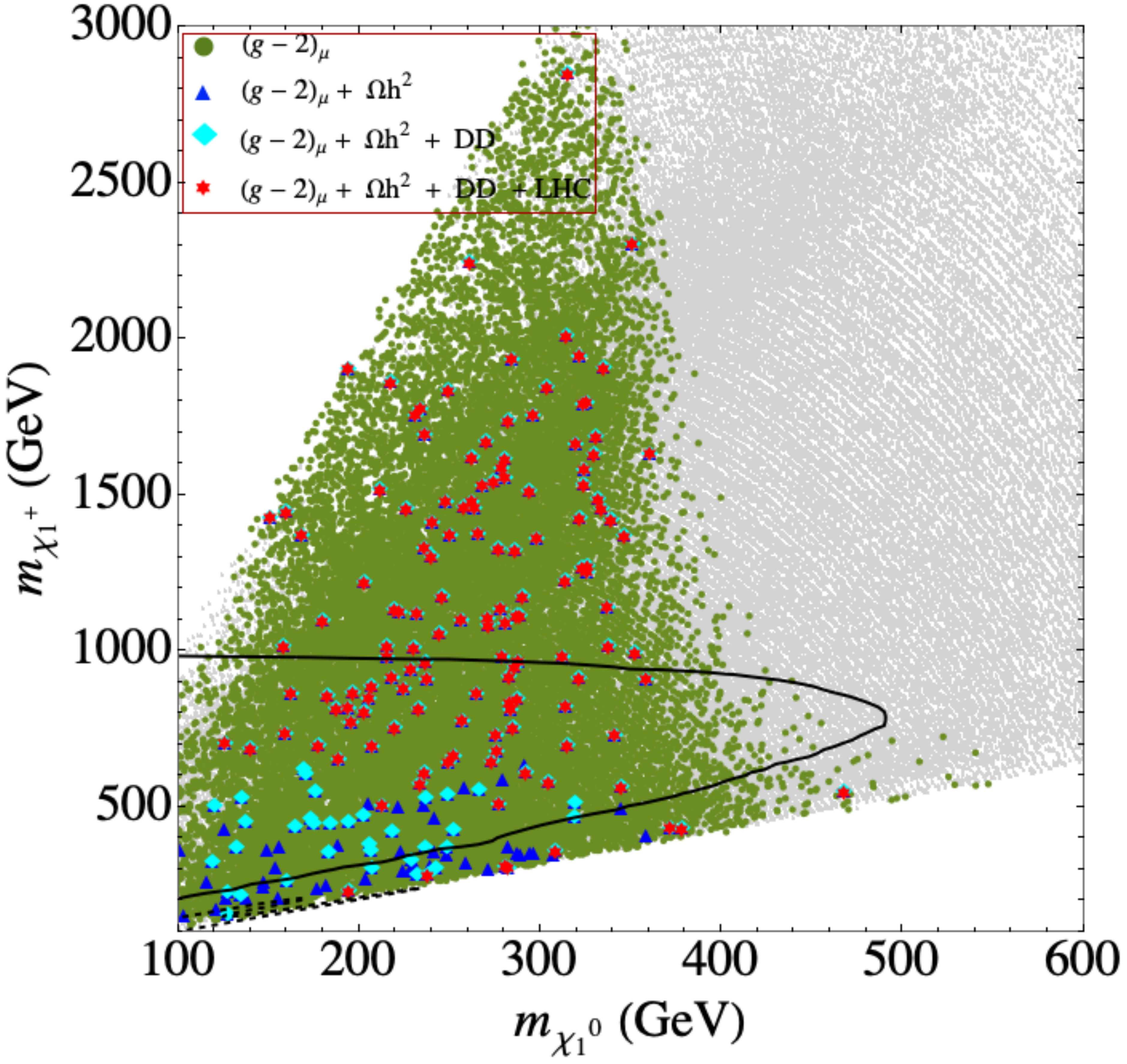


The left-sleptons and sneutrinos are close in mass to the LSP

# Slepton Co-annihilation: Case-L

Current $(g-2)_\mu$ limit





Large $\mathrm{BR}(\tilde{\chi}_1^\pm \to \tilde{\tau}_1 \nu_\tau)$ and $\mathrm{BR}(\tilde{\chi}_2^0 \to \tilde{\tau}_1 \tau)$ , $\mathbf{BR}(\tilde{\chi}_2^0 \to \tilde{\nu}\nu)$

( *3l* + missing $E_T$ ) exclusion limit weakens ...

## $(g-2)_\mu$

- Large discrepancy from the SM (more than $3\sigma$):

  $a_\mu^{exp} - a_\mu^{SM} = (28.02 \pm 7.37) \times 10^{-10}$.

  Keshavarzi, Nomura, Teubner '19

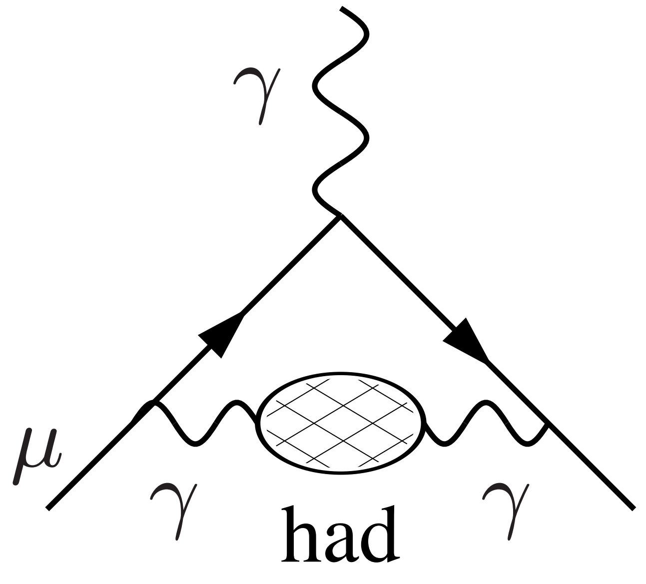
- Important probe for new physics. $\frac{\delta a_l}{a_l} \sim \frac{m_l^2}{\Lambda^2}$.

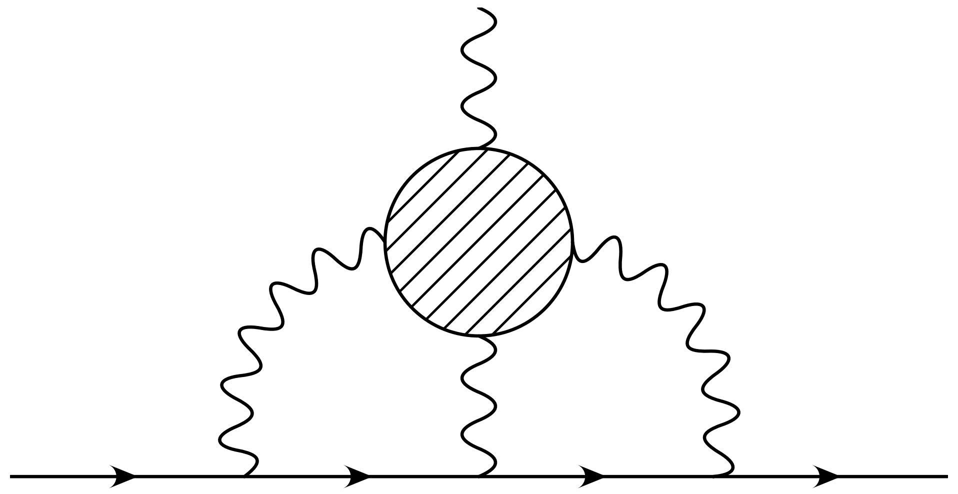
- SM contributions : QED, weak, hadronic vacuum polarization, hadronic light by light scattering.

- QED : complete calculation upto 5 loops. EW : two loops.

  Aoyama, Hayakawa, Kinoshita, Nio '17, Ishikawa, Nakazawa, Yasu '18, Heinemeyer, Stökinger, Weiglein '04

- Uncertainty dominated by non-perturbative, hadronic sector.





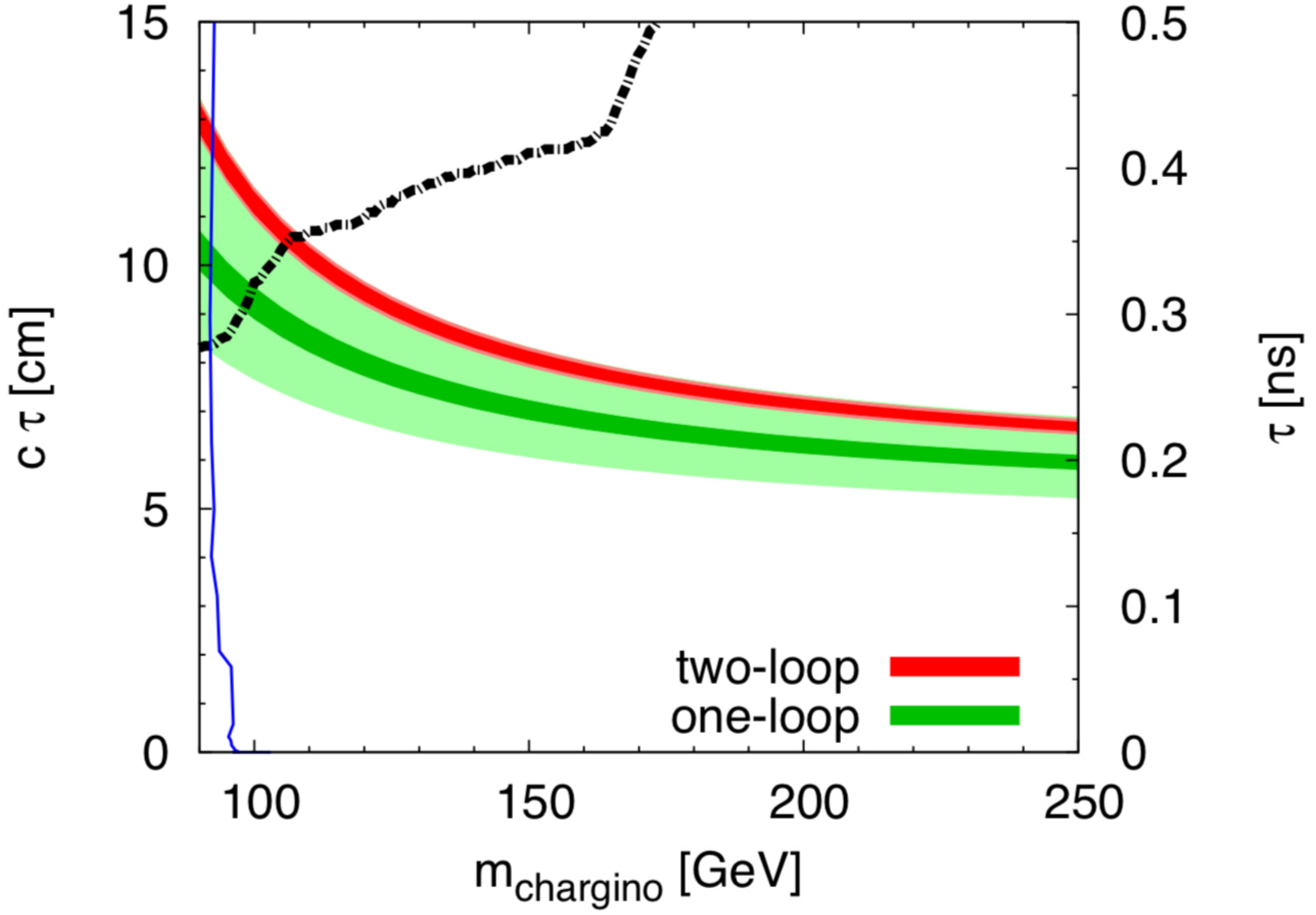


Figure 6: The lifetime of charged wino evaluated by using $\delta m$ at the one-loop (green band) and two-loop (red band). We neglected the next-to-leading order corrections to the lifetime of the charged wino estimated in terms of the pion decay rate, which is expected to be a few percent correction. The black chain line is the upper limit on the lifetime for a given chargino mass by the ATLAS collaboration at 95 % CL ($\sqrt{s} = 7$ TeV, $\mathcal{L} = 4.7$ fb$^{-1}$) [28]. The blue line shows the constraints which are given by the LEP2 constraints [30]–[33].